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PRACA DOKTORSKA

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Kompleksowa ocena pacjentów po leczeniu złamań kości piętowej polską modyfikacją metody Ilizarowa

Comprehensive assessment of patients after treatment of calcaneal fractures using the Polish modification of the Ilizarov method

Praca napisana pod kierunkiem
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SPIS TREŚCI

SPIS TABEL I RYCIN

WYKAZ PUBLIKACJI WCHODZĄCY W SKŁAD DOKTORATU

Publikacja I

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Publikacja II

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Publikacja III

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Publikacja IV

Morasiewicz P, **Pelc M**, Tomczyk Ł, Kochańska-Bieri J, Bobiński A, Pili D, Reichert P Clinical and Radiological Assessment of the Polish Modification of the Ilizarov External Fixator for the Treatment of Intra-Articular Calcaneal Fractures. Adv. Clin. Exp. Med. 2025. https://doi.org/10.17219/acem/192772 (IF 2.1, MNiSW 70 pkt)

1. WSTĘP

Złamania kości piętowej stanowią około 2% wszystkich złamań i obejmują 50–60% przypadków złamań w obrębie kości stępu [I/1-5: IV/1,4]. W większości przypadków są one wynikiem urazów wysokoenergetycznych, takich jak upadki z dużej wysokości na kończyny dolne czy wypadki komunikacyjne [II/1-4]. Złamania wewnątrzstawowe, stanowiące aż 75% wszystkich przypadków złamań kości piętowej, od dawna są istotnym wyzwaniem terapeutycznym w ortopedii [I/1-4; II/2,4–7; III/1,3,5,6; IV/1–4,6,7,10–13]. U pacjentów ze złamaniami kości piętowej dość często dochodzi do powikłań, u części pacjentów odnotowywano złe wyniki końcowe leczenia i brak możliwości powrotu do nauki lub pracy zarobkowej [I/1-4; II/2,4–7; III/1,3,5,6; IV/1–4,6,7,10–13]. W przeszłości standardowym postępowaniem w leczeniu wewnątrzstawowych złamań kości piętowej była zamknięta repozycja z następczym unieruchomieniem w gipsie bądź stabilizacja odłamów kostnych za pomocą drutów Kirschnera lub grotów Steinmanna [I/2,6,10]. Postęp technologiczny przyczynił się do upowszechnienia techniki otwartej repozycji i wewnętrznej stabilizacji złamań kości piętowej za pomocą płyty (ORIF) lub gwoździa śródszpikowego [III/1–13]. Pomimo postępu w leczeniu, wspomniane metody nadal obciążone były znacznym ryzykiem powikłań, które mogło wynosić aż 33%. Wśród najczęstszych komplikacji wymienia się infekcje, opóźnione gojenie ran, martwicę tkanek miękkich oraz destabilizację implantów [I/1–3,6,7; II/6,11–13]. Według niektórych badań techniki minimalnie inwazyjne oraz przezskórne procedury repozycji i stabilizacji mogą stanowić skuteczniejszą alternatywę dla klasycznych metod otwartej repozycji i stabilizacji złamań kości piętowej [II/24].

W leczeniu złamań wewnątrzstawowych kości piętowej wykorzystywana jest metoda Ilizarowa [I/2,3,5–9,12–14]. Dotychczas stosowane konstrukcje stabilizatora Ilizarowa, w leczeniu złamań kości piętowej, wymagały użycia przynajmniej trzech drutów Kirschnera do stabilizacji stopy [I/2,3,5–9,12–14]. Polska modyfikacja konstrukcyjna stabilizatora Ilizarowa do leczenia złamań kości piętowej została wprowadzona we Wrocławiu w latach 90 XX wieku [I/4; IV/4,15]. Zapewnia ona skuteczną repozycję i stabilizację fragmentów kości piętowej w sposób mniej inwazyjny, eliminując konieczność otwartego dostępu oraz ograniczając stabilizację stopy i kości piętowej do jednego drutu Kirschnera, mocowanego do półpierścienia piętowego [I/4; IV/4,15].

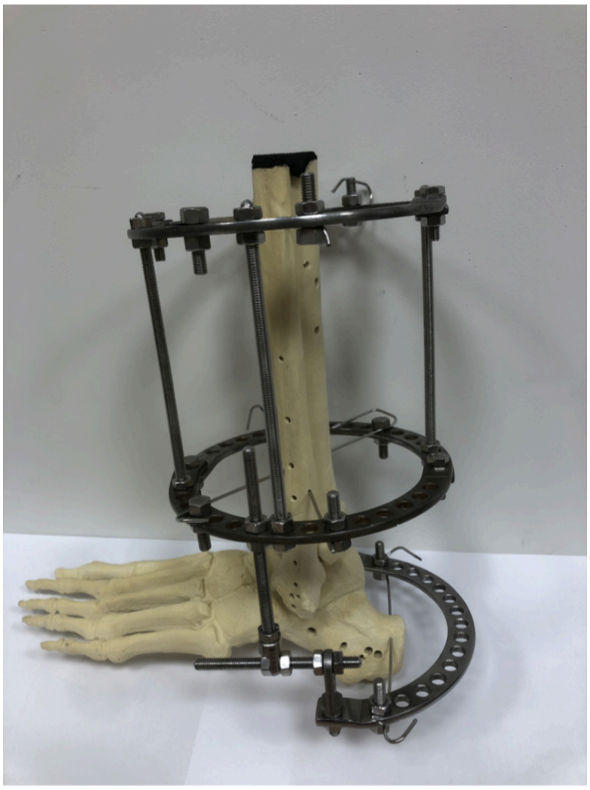
Nie w pełni poznany i zbadany jest temat oceny wyników leczenia złamań kości piętowej polską modyfikacją metody Ilizarowa. Dotychczas dostępne było tylko jedno badanie przedstawiające kliniczne i radiologiczne wyniki zamkniętej repozycji i stabilizacji polską modyfikacją metody Ilizarowa złamań kości piętowej [I/4; IV/4]. Autorzy tego artykułu ocenili 11 pacjentów ze złamaniami kości piętowej leczonymi metodą Ilizarowa i przeanalizowali wybrane parametry kliniczne i radiologiczne (skala Rowesa, skala Olerud-Molander Ankle, kąt Böhlera, kąt infleksji) [I/4; IV/4]. Zarówno parametry kliniczne, jak i radiologiczne uległy poprawie po leczeniu [I/4; IV/4]. Brakuje również kompleksowych analiz obejmujących wyniki kliniczne, funkcjonalne, radiologiczne oraz ocenę równowagi, rozkładu obciążeń kończyn dolnych i mechaniki chodu pacjentów ze złamaniami kości piętowej poddanych tej metodzie leczenia.

2. CELE PRACY

1. Ocena równowagi i rozkładu obciążeń kończyn dolnych u pacjentów po leczeniu złamań kości piętowej z zastosowaniem polskiej modyfikacji metody Ilizarowa.
2. Analiza parametrów chodu u pacjentów ze złamaniem kości piętowej leczonych polską modyfikacją metodą Ilizarowa.
3. Ocena kliniczna i radiologiczna pacjentów po leczeniu złamań kości piętowej polską modyfikacją metodą Ilizarowa.
4. Analiza funkcjonalna pacjentów po zastosowaniu polskiej modyfikacji metody Ilizarowa w leczeniu złamania kości piętowej.

3. Materiały i metody

Do leczenia złamań kości piętowej zastosowano zewnętrzny stabilizator w polskiej modyfikacji metody Ilizarowa (rycina 1), składający się z dwóch pierścieni mocowanych do kości piszczelowej i strzałkowej drutami Kirschnera oraz półpierścienia piętowego mocowanego do kości piętowej pojedynczym drutem Kirschnera. Operacje przeprowadzano techniką zamkniętą, bez otwartego dostępu do miejsca złamania. Pacjenci otrzymywali profilaktykę antybiotykową w postaci jednej dawki Biofazoliny (1 g; BIOTON, Warszawa, Polska) podanej dożylnie. Najpierw do kości piszczelowej i strzałkowej mocowano dwa pierścienie za pomocą drutów Kirschnera. Następnie pod kontrolą fluoroskopii wprowadzano w guz piętowy jeden 2-milimetrowy drut Kirschnera od strony bocznej do przyśrodkowej, w najbardziej grzbietowy i proksymalny fragment kości piętowej. Półpierścień piętowy umieszczano za stopą, stabilizując go na wprowadzonym drucie Kirschnera, a następnie łączono z dolnym pierścieniem na podudziu za pomocą dwóch łączników. Każdy łącznik składał się z dwóch połączonych ze sobą prętów gwintowanych, które umożliwiały dystrakcję oraz przemieszczenie grzbietowe odłamów kości piętowej. Po zamontowaniu stabilizatora przeprowadzano repozycję zamkniętą złamania pod kontrolą fluoroskopii, a ligamentotaksja, pośrednia repozycja fragmentów kostnych oraz specyficzna konstrukcja stabilizatora Ilizarowa i lokalizacja druta Kirschnera w kości piętowej, pozwalała na uzyskanie prawidłowego ustawienia odłamów kostnych bez konieczności otwartego dostępu do kości piętowej. Polska modyfikacja metody Ilizarowa dodatkowo pozwala na rozciąganie oraz korektę ustawienia odłamów w płaszczyznach czołowej i strzałkowej oraz na korekcję deformacji koślawej lub szpotawej pięty. Konstrukcja stabilizatora pozwala również na wykonanie artrodiatazy stawu skokowego górnego i skokowo-piętowego, co jest korzystne w procesie leczenia.

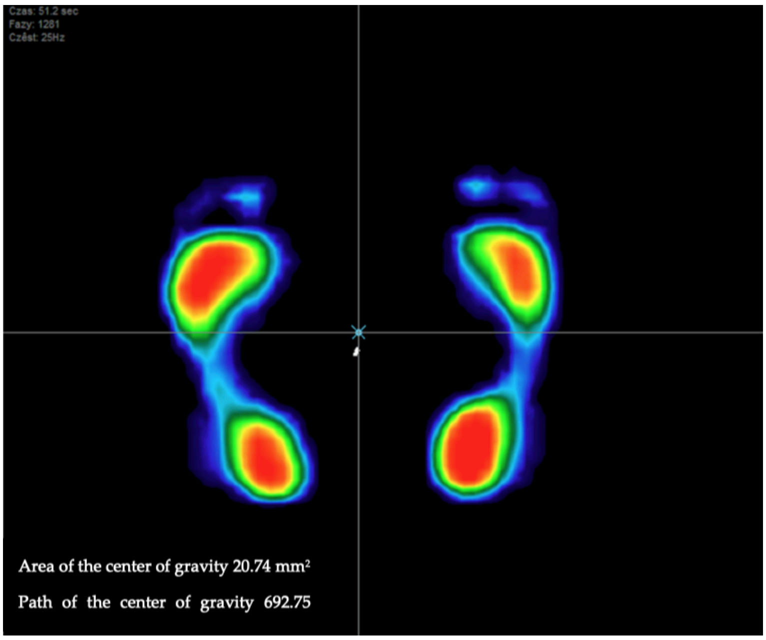


Rycina 1 - Model przedstawiający stabilizator Ilizarowa w polskiej modyfikacji wykorzystywany do leczenia złamań kości piętowej.

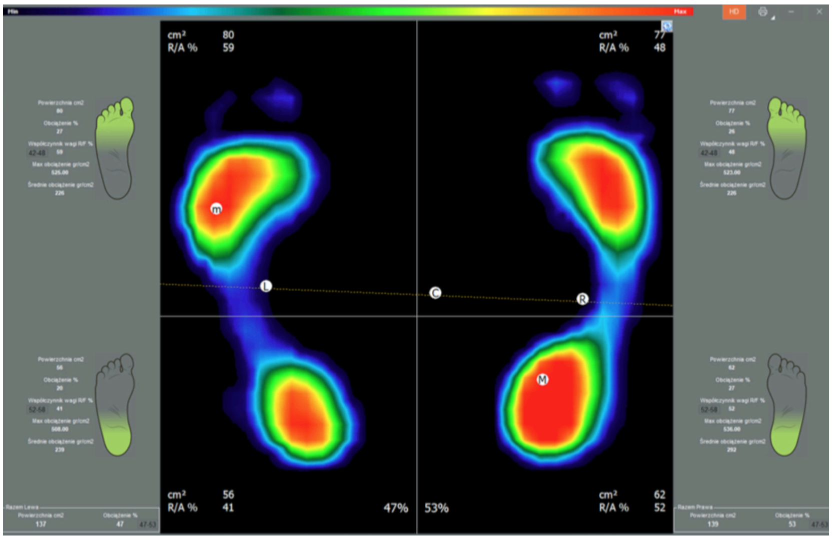
Pacjenci poddawani byli wczesnej rehabilitacji, która obejmowała rozpoczęcie nauki chodu z kulami z częściowym obciążeniem operowanej kończyny w pierwszej dobie po operacji. Stopniowe zwiększanie obciążenia była uzależniona od indywidualnej tolerancji bólowej. W przypadku prawidłowego gojenia ran pacjentów wypisywano do domu w pierwszej dobie po zabiegu. Postępy leczenia monitorowano według ujednoliconego protokołu, obejmującego regularne wizyty kontrolne oraz badania obrazowe. Zdjęcia rentgenowskie wykonywano w dniu operacji, po dwóch i sześciu tygodniach, a następnie w czterotygodniowych odstępach do momentu uzyskania całkowitego zrostu kostnego. Zrost kostny określono na podstawie dowodów radiologicznych (obecność kostniny, przejście beleczkowania lub ciągłość warstwy korowej przez linię złamania) i klinicznych (brak bólu w badaniu fizykalnym, brak patologicznej ruchomości odłamów kostnych, bezbolesne obciążanie kończyny). Po stwierdzeniu zrostu kostnego stabilizator był luzowany i umożliwiano pełne obciążenie kończyny. Całkowite usunięcie stabilizatora następowało tydzień później, pod warunkiem braku wtórnych przemieszczeń odłamów kostnych w kontrolnym badaniu radiologicznym.

3.1. PUBLIKACJA I

W pracy przedstawiono retrospektywną ocenę równowagi i rozkładu obciążeń ciała u pacjentów ze złamaniami wewnątrzstawowymi kości piętowej leczonych polską modyfikacją metody Ilizarowa w latach 2021-2022 (ryciny 2-3).



Rycina 2 - Grafika testu równowagi.



Rycina 3 - Procentowy rozkład masy ciała na kończynach dolnych.

Kryteriami włączenia do badania były: złamanie śródstawowe kości piętowej leczone polską modyfikacją metody Ilizarowa, okres obserwacji przekraczający 2 lata, kompletna dokumentacja oceny pedobarograficznej, medycznej i radiologicznej oraz brak współistniejących schorzeń kończyn dolnych. Pisemna, świadoma zgoda na udział w badaniu.

Kryteriami wykluczenia z badania były: złamania wewnątrzstawowe kości piętowej leczone innymi metodami niż metodą Ilizarowa, obserwacja krótsza niż 2 lata, niepełna dokumentacja oceny pedobarometrycznej, medycznej i radiologicznej, obecne współistniejące schorzenia kończyn dolnych oraz brak pisemnej zgody pacjenta na udział w badaniu. Udział w badaniu był dobrowolny, a pacjenci zostali poinformowani o możliwości wycofania się na każdym etapie. W celu przeprowadzenia badania uzyskano zgodę lokalnej komisji bioetycznej (UO/0023/KB/2023).

Na podstawie kryteriów włączenia i wykluczenia badaniem objęto 21 pacjentów (7 kobiet, 14 mężczyzn) w wieku od 25 do 67 lat (średni wiek 47 lat), ze wskaźnikiem masy ciała 24–40 (średnio 28), wzrostem 152–188 cm (średnio 171 cm), masą ciała 61–130 kg (średnio 81 kg). W skład grupy eksperymentalnej wchodziły przypadki złamań kości piętowej sklasyfikowane według Sandersa, obejmujące typ 2 (n = 3), typ 3 (n = 5) oraz typ 4 (n = 13). Wszystkie operacyjne zostały przeprowadzone przez tego samego ortopedę, który stosował polską modyfikację metody Ilizarowa jako metodę leczenia złamań kości piętowej. Dwudziestu jeden zdrowych ochotników stanowiło grupę kontrolną, która została dobrana pod względem płci, wieku i BMI.

Do przeprowadzenia badań pedobarograficznych wykorzystano system FreeMED MAXI (rycina 4) stworzony przez firmę SensorMedica (Guidonia Montecelio, Rzym, Włochy).

Urządzenie składało się z platformy o wymiarach 63,5 × 70 cm (z aktywną powierzchnią pomiarową 50 × 60 cm), dwóch mat pomocniczych oraz komputera wyposażonego w dedykowane oprogramowanie. System umożliwiał precyzyjny pomiar nacisku stóp do wartości 150 N/cm² z częstotliwością próbkowania 300 Hz. Czujniki zastosowane w platformie (n = 3000) były pokryte warstwą złota, co zapewniało ich wysoką czułość oraz trwałość [I/26-29,35,56].

Rycina 4 - Platforma pedobarograficzna FreeMED MAXI (SensorMedica).

Przed przystąpieniem do badań uczestnicy otrzymywali instrukcje dotyczące przyjęcia odpowiedniej pozycji. Pomiar wykonywano w pozycji stojącej, przy naturalnym ustawieniu stóp (rotacja zewnętrzna 5–10°) i swobodnie opuszczonych rękach wzdłuż tułowia. Czas trwania analizy równowagi wynosił 51,2 sekundy. Po stabilizacji pozycji trwającej 5 sekund rejestrowano rozkład obciążeń ciała. Podczas testów badani utrzymywali wzrok na stałym punkcie umiejscowionym na wysokości ich oczu, a każda sesja składała się z trzech pomiarów. Każdy uczestnik został poddany trzykrotnemu pomiarowi, a do analizy wykorzystano średnią wartość z uzyskanych wyników.

Równowagę oceniano na podstawie drogi środka ciężkości, zdefiniowanej przez dystans jaką przebył środek ciężkości podczas całego czasu trwania analizy ,wyrażonej w mm [I/15-20,30]. Do analizy równowagi zastosowano również pole powierzchni maksymalnych odchyleń środka ciężkości, określony jako pole (w mm²) ograniczone przez punkty jego największych przemieszczeń we wszystkich kierunkach w czasie całego pomiaru [I/15-20,30].

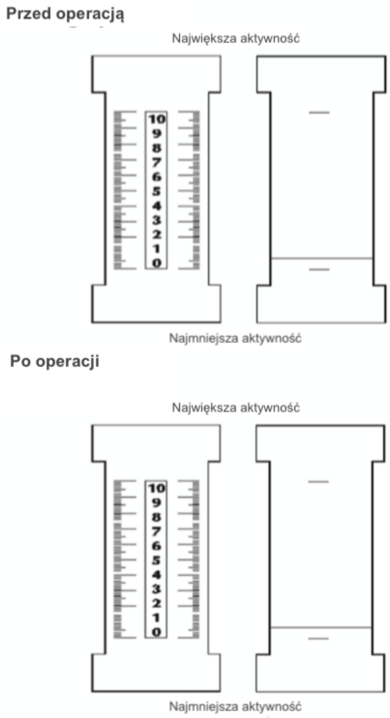
Rozkład obciążeń kończyn dolnych oceniano w %. Oceniano rozkład obciążeń na całą kończynę dolną chorą i zdrową oraz oceniano rozkład % obciążenia przodostopia i tyłostopia chorej i zdrowej kończyny. W grupie kontrolnej zdrowych osób przyjęto, że dominująca kończyna jest kończyną zdrową, natomiast niedominująca kończyna jest kończyną chorą [I/17,18,21]. Wyniki uzyskane w grupie pacjentów leczonych z powodu złamania kości piętowej metodą Ilizarowa porównano z danymi grupy kontrolnej zdrowych ochotników. Analizie poddano rozkład obciążenia kończyny operowanej względem niedominującej kończyny grupy kontrolnej oraz kończyny nieoperowanej względem kończyny dominującej osób zdrowych.
Analizę statystyczną przeprowadzono z wykorzystaniem programu Statistica w wersji 13.1. Do sprawdzenia normalności rozkładu wykorzystano test Shapiro–Wilka. Zmienne ciągłe były przedstawiane jako średnia (±SD). Test Levene'a został użyty do oceny równości wariancji w dwóch zestawach pomiarów. Do porównania zmiennych ilościowych wykorzystano test t-Studenta. Poziom istotności statystycznej przyjęto na poziomie $p < 0,05$.

3.2. Publikacja II

Badanie retrospektywne obejmowało analizę pacjentów ze złamaniami wewnątrzstawowymi kości piętowej, którzy w latach 2021–2022 byli leczeni w jednym ośrodku z zastosowaniem polskiej modyfikacji metody Ilizarowa. Szczegółową charakterystykę grupy badawczej przedstawiono w publikacji I.
Do badania włączano pacjentów z minimalnym okresem obserwacji wynoszącym dwa lata, u których operację przeprowadzał ten sam ortopeda. Warunkiem uczestnictwa była również kompletna dokumentacja medyczna zawierająca dane dotyczące oceny funkcjonalnej, aktywności fizycznej, zakresu ruchu w stawie skokowym, brak innych patologii w obrębie kończyn dolnych oraz świadomą zgodę pacjenta, który mógł wycofać się z badania na każdym jego etapie. Osoby niespełniające tych warunków nie zostały zakwalifikowane do badania. Badanie uzyskało zgodę lokalnej komisji bioetycznej (Nr UO/0023/KB/2023) i przeprowadzono je zgodnie z Deklaracją Helsińską.
U wszystkich pacjentów przeprowadzono diagnostykę obrazową, obejmującą zdjęcia RTG stopy w projekcjach AP i bocznej, zdjęcie osiowe kości piętowej oraz tomografię komputerową stopy i stawu skokowego. Do momentu interwencji chirurgicznej kończynę zabezpieczano za pomocą opatrunku gipsowego na oddziale ratunkowym. Stabilizację złamania kości piętowej metodą Ilizarowa przeprowadzał doświadczony ortopeda, a operację wykonywano od 3 do 5 dni po urazie, zależnie od dostępności bloku operacyjnego i obecności operatora.

Szczegółowy opis budowy stabilizatora Ilizarowa, protokołu rehabilitacji oraz kontroli pooperacyjnej opisano we wstępie.

W niniejszym badaniu przeprowadzono analizę funkcji stopy oraz poziomu aktywności fizycznej uczestników. Oceny dokonano przy użyciu kwestionariusza wskaźnika funkcji stopy w wersji zrewidowanej (FFI-R) [II/25,26] oraz trzech skal aktywności fizycznej: 10-punktowej skali UCLA [II/27], 10-punktowej wizualnej analogowej skali aktywności (VAS) (rycina 5) [II/28] oraz 6-punktowej skali Grimby'ego [II/29]. Dokonano porównania parametrów funkcjonalnych ocenianych w okresie przedoperacyjnym oraz w kontroli odległej po leczeniu.



Rycina 5 - Analogowa, wizualna skala aktywności fizycznej (VAS).

Kwestionariusz FFI-R, opracowany w celu kompleksowej oceny funkcji stopy, zawiera 68 pytań podzielonych na pięć podskal: ból (11 pozycji), sztywność (8 pozycji), trudności funkcjonalne (20 pozycji), ograniczenia aktywności (10 pozycji) oraz funkcjonowanie społeczne (19 pozycji). Skala odpowiedzi została dostosowana do każdej podskali, przy czym wartości wyższe wskazywały na większe zaburzenia funkcjonalne.

Poziom aktywności fizycznej oceniono na podstawie skali UCLA, w której każda z dziesięciu kategorii odpowiadała określonemu zakresowi aktywności, od minimalnej (np. siedzący tryb życia) po bardzo intensywną (np. regularny wysiłek fizyczny). Respondenci samodzielnie deklarowali swoje poziomy aktywności, a ich odpowiedzi były klasyfikowane zgodnie z ustalonymi kryteriami skali.

Kolejną skalą oceniającą aktywności fizycznej była skala VAS (wizualna analogowa skala aktywności fizycznej), która służyła do subiektywnej klasyfikacji aktywności w określonym okresie czasu [II/28]. Skala ta miała dwa punkty graniczne – wartość 0 odnosiła się do całkowitego braku ruchu, oznaczając stan bez jakiejkolwiek aktywności fizycznej, natomiast wartość 10 oznaczała maksymalny poziom aktywności, obejmujący intensywne i systematyczne ćwiczenia. Badani określali swój poziom aktywności poprzez zaznaczenie odpowiedniego punktu na skali, co pozwalało na ilościową analizę ich codziennej aktywności.
W skali Grimby'ego opartej na samoocenie uczestników, badani odpowiadali na pytanie dotyczące ich zwyczajowej aktywności, przypisując się do jednej z sześciu kategorii, odzwierciedlających różne poziomy aktywności – od braku jakiejkolwiek aktywności po regularne intensywne treningi. Przed rozpoczęciem wypełniania kwestionariusza wszystkim uczestnikom przekazano szczegółowe instrukcje dotyczące prawidłowego wypełnienia formularza, ponadto respondenci mieli możliwość uzyskania dodatkowych objaśnień w przypadku trudności ze zrozumieniem pytań w czasie wypełniania kwestionariusza.
Zakres ruchomości stawu skokowego oceniano przy użyciu goniometru, dokonując pomiarów zarówno w kończynie poddanej operacji, jak i w kończynie zdrowej. Analiza obejmowała wartości dla zgięcia grzbietowego i podeszwowego oraz ruchów inwersji i ewersji, a uzyskane wyniki wyrażano w stopniach.
Dane poddano analizie statystycznej w programie Statistica 13.3. Test Shapiro-Wilka posłużył do oceny normalności rozkładu, natomiast test rang Wilcoxona zastosowano do analizy zmiennych ilościowych. Za próg istotności statystycznej przyjęto $p < 0,05$.

3.3. PUBLIKACJA III

W ramach retrospektywnej analizy oceniono chód u pacjentów, u których w latach 2021–2022 przeprowadzono leczenie operacyjne złamań wewnątrzstawowych kości piętowej z wykorzystaniem polskiej modyfikacji metody Ilizarowa. Do badania włączono osoby spełniające określone kryteria: leczenie operacyjne metodą Ilizarowa, co najmniej dwuletnią obserwację, pełną dokumentację medyczną i obrazową, kompletne wyniki analizy chodu oraz brak współistniejących urazów lub schorzeń kończyn dolnych. Wszystkie operacje były wykonane przez tego samego ortopedę. Osoby, które nie spełniły kryteriów, nie zostały uwzględnione w badaniu. Każdy pacjent przed przystąpieniem do analizy otrzymał informacje o jej dobrowolnym charakterze i możliwości rezygnacji na dowolnym etapie. Projekt badawczy został zatwierdzony przez komisję bioetyczną (UO/0023/KB/2023). Dokładny opis układu przestrzennego stabilizatora zewnętrznego oraz protokołu obserwacji pooperacyjnej opisano we wstępie. Po zastosowaniu kryteriów włączenia i wykluczeń do badania zakwalifikowano 21 pacjentów (7 kobiet i 14 mężczyzn) w wieku od 25 do 67 lat, ze średnią wieku 47 lat. Ich BMI mieściło się w zakresie 24–40 (średnia 28), wzrost wynosił od 152 do 188 cm (średnia 171 cm), a masa ciała wahała się między 61 a 130 kg (średnia 81 kg). U dwóch pacjentów stwierdzono złamania otwarte. Grupę kontrolną utworzyło 19 zdrowych ochotników, dobranych pod względem płci, ale wykazujących różnice w wieku i BMI. Pacjentów w grupie badawczej podzielono według klasyfikacji Sandersa na trzy przypadki złamań typu II, pięć typu III i trzynaście typu IV. Stabilizator Ilizarowa utrzymywano średnio przez 88 dni (od 67 do 105 dni). Ocena chodu została przeprowadzona przy użyciu BTS G-SENSOR (BTS Bioengineering Corp., Quincy, MA, USA), kompaktowego urządzenia (70 × 40 × 18 mm, 37 g) wyposażonego w trójosiowy akcelerometr, trójosiowy magnetometr, żyroskop o regulowanej czułości oraz moduł GPS, (rycina 6). Dane były rejestrowane z częstotliwością do 100 Hz, a następnie przesyłane bezprzewodowo do komputera. Analiza odbywała się za pomocą dedykowanego oprogramowaniu BTS G-Studio, które umożliwia obliczenie czasowo-przestrzennych parametrów chodu oraz ocenę symetrii pomiędzy kończynami dolnymi. Przed rozpoczęciem badania uczestnicy otrzymali szczegółowe instrukcje oraz poddano ich pomiarom wzrostu i masy ciała. Sensor BTS G-SENSOR umieszczono na wysokości L5 przy użyciu półelastycznego pasa. Urządzenie charakteryzuje się wysoką precyzją i powtarzalnością pomiarów, co potwierdza współczynnik zmienności 2,5% oraz współczynnik korelacji w zakresie 0,90–0,99 [III/26-27].

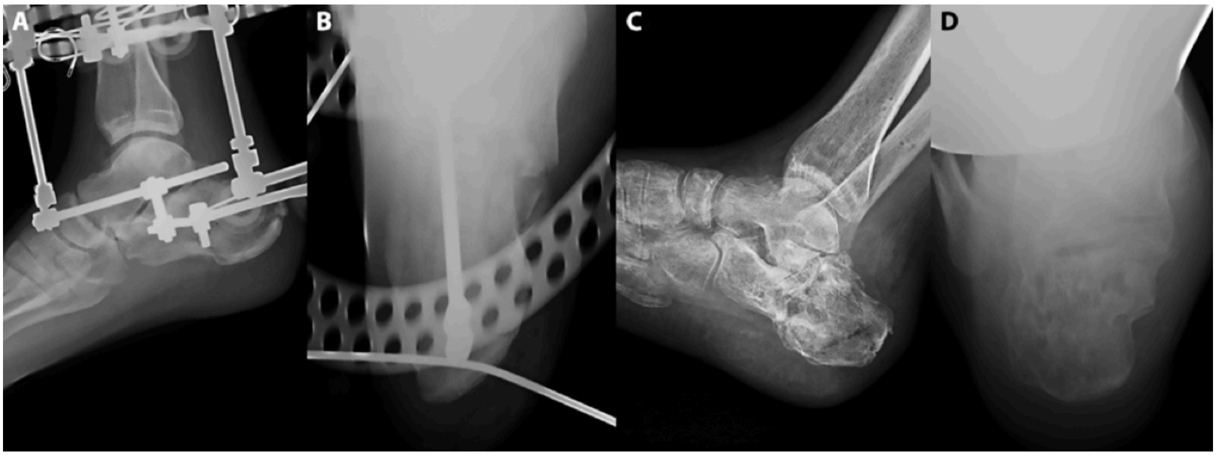
Rycina 6 - G-sensor przymocowany do ciała pacjenta.

Testy przeprowadzono według protokołu WALK. Po krótkiej stabilizacji czujnika uczestnicy przechodzili 8 metrów, zawracali i wracali do punktu początkowego. Badanie odbywało się boso, w naturalnym tempie. Każda osoba wykonała trzy pomiary, a ich średnia wartość była uwzględniona w analizie. Wyniki przetwarzano w programie BTS G-STUDIO, który analizował parametry czasowo-przestrzenne chodu. W tym badaniu oceniano następujące parametry chodu: czas trwania cyklu chodu (s), długość kroku (%), czas trwania fazy podporu (%), czas trwania fazy przenoszenia (%), czas trwania fazy podwójnego podporu (%) , czas trwania fazy pojedynczego podporu (%), kadencja (kroki/min), prędkość (m/s), długość kroku (m). Porównano kończynę zdrową i leczoną w grupie po operacji złamania kości piętowej oraz zestawiono wyniki z danymi zdrowych ochotników. Zestawiono także parametry zdrowej kończyny grupy badawczej z dominującą kończyną zdrowych osób oraz kończynę po operacji z kończyną niedominującą grupy kontrolnej. Dodatkowo, poziom bólu oceniono za pomocą 10-stopniowej wizualnej skali analogowej (VAS). W badaniu radiologicznym analizowano kąty Böhlera i Gissane'a przed operacją oraz w długoterminowej obserwacji po leczeniu.
Dane poddano analizie statystycznej przy użyciu programu Statistica 13.1. Normalność rozkładu zmiennych oceniano testem Shapiro–Wilka. Do porównań zmiennych ilościowych zastosowano test t-Studenta, a poziom istotności statystycznej ustalono na $p < 0,05$.

3.4. PUBLIKACJA IV

W tym retrospektywnym badaniu prowadzonym w dwóch akademickich ośrodkach analizowano 30 pacjentów ze śródstawowymi złamaniami kości piętowej leczonych polską modyfikacją metody Ilizarowa. Do badania włączono pacjentów z klasyfikowanym według Sandersa złamaniem kości piętowej (typ II, III lub IV), leczonych polską modyfikacją metody Ilizarowa. Wymagano kompletnej dokumentacji medycznej i radiologicznej, co najmniej 2-letniej obserwacji oraz zgody pacjenta. Wykluczano osoby z niepełną dokumentacją lub krótszym okresem obserwacji. Uczestnicy byli informowani o dobrowolnym udziale, a badanie zostało zatwierdzone przez Komisję Bioetyczną Uniwersytetu Opolskiego (UO/0023/KB/2023).
W oparciu o powyższe kryteria do badania zakwalifikowano 27 pacjentów, spośród których 2 to kobiety, a 25 to mężczyźni. Wiek wynosił od 28 do 73 lat, przy czym średnia wieku w badanej grupie wyniosła 50,5 roku. Diagnostyka złamań kości piętowej obejmowała zdjęcia RTG (w projekcjach AP, bocznej i osiowej) oraz tomografię komputerową (rycina 7). W analizowanej grupie stwierdzono 4 przypadki złamań typu II, 6 typu III i 17 typu IV według klasyfikacji Sandersa. U pacjentów ze złamaniami otwartymi (3 osoby) rany były oczyszczane i

zszywane, a złamanie było wstępnie unieruchamiane w longecie gipsowej. Dodatkowo stosowano antybiotykoterapię (klindamycyna przez 14 dni – początkowo dożylnie, a następnie doustnie). Szczegółowe informacje dotyczące techniki operacyjnej, przestrzennego ustawienia stabilizatora oraz prowadzonego postępowania pooperacyjnego, w tym zasady rehabilitacji i kontrolnych badań radiologicznych, zostały opisane we wstępie.



Rycina 7 - Pacjent w trakcie (a,b) i po (c,d) leczeniu złamania śródstawowego kości piętowej polską modyfikacją metody Ilizarowa.

Oceniane parametry analizowano na podstawie dostępnej dokumentacji medycznej, radiologicznej oraz wypełnionych kwestionariuszy. W badaniu poddano analizie ocenę bólu na podstawie 10-punktowej wizualnej skali analogowej VAS, wyniki funkcjonalne według 100-punktowej skali AOFAS, poziom satysfakcji pacjentów z leczenia na podstawie 4-stopniowej skali oraz stosowanie leków przeciwbólowych. Dodatkowo uwzględniono czas utrzymania stabilizatora Ilizarowa na kończynie dolnej, długość hospitalizacji oraz czas trwania operacji. Analizowano również deklarowaną gotowość pacjentów do ponownego skorzystania z tej metody leczenia, wartości kątów Böhlera, infleksji i Gissane'a, częstość występowania powikłań i zmian zwyrodnieniowych, w tym infekcje w miejscach wprowadzenia drutów, infekcje uogólnione, martwicę skóry i tkanki podskórnej, opóźnione gojenie ran oraz obrzęk. Oceniano także przypadki wymagające ponownej operacji oraz konieczność przeprowadzenia dodatkowych procedur chirurgicznych, takich jak artrodeza, osteotomia czy amputacja. Do powikłań zaliczono również uszkodzenia naczyń krwionośnych i nerwów, konieczność stosowania obuwia ortopedycznego lub wkładek po leczeniu, destabilizację zespolenia, uszkodzenie implantu, wtórne przemieszczenie odłamów kostnych oraz brak zrostu kostnego. Ocena zmian zwyrodnieniowych została przeprowadzona na podstawie zdjęć radiologicznych wykonanych podczas długoterminowej wizyty kontrolnej. Analizowane stawy obejmowały staw skokowy górny, skokowo-piętowy, skokowo-łódkowy oraz piętowo-sześcienny.

Analiza kątów radiologicznych obejmowała ocenę kąta Böhlera, infleksji i Gissane'a na bocznych zdjęciach RTG stopy. Kąt Böhlera jest zawarty pomiędzy linią łączącą najwyższy punkt wyrostka przedniego i powierzchni stawowej skokowej tylnej kości piętowej i linią styczną do górnej powierzchni guza piętowego, a jego prawidłowa wartość wynosiła 20–40°. Kąt infleskji zdefiniowano jako kąt utworzony przez guz piętowy, kość sześcienną oraz głowy kości śródstopia. Prawidłowy zakres wynosi 145–150°. Kąt Gissane'a zdefiniowano jak kąt między opadającą i wznoszącą częścią górnej powierzchni kości piętowej, wynosił prawidłowo 120–145°.

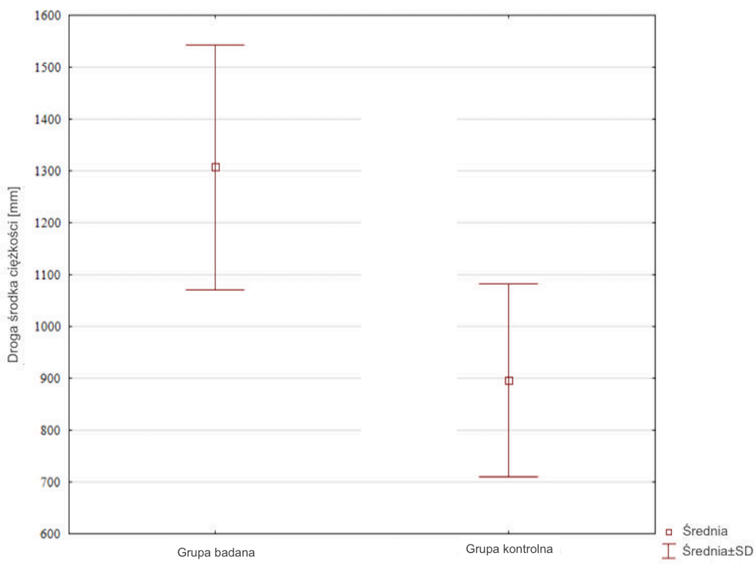
Dane analizowano statystycznie za pomocą programu Statistica v. 13. Normalność rozkładu zmiennych oceniano testem Shapiro-Wilka**.** Do porównania zmiennych ilościowych zastosowano test rang Wilcoxona**.** W przypadku wielokrotnych porównań stosowano korektę Bonferroniego**.** Poziom istotności statystycznej ustalono na $p < 0,05$**.**

4. PODSUMOWANIE WYNIKÓW

W pierwszej publikacji średnia droga środka ciężkości w grupy badanej wynosiła 1307,31 mm i była statystycznie dłuższa niż w grupie kontrolnej (896,34mm), ($p<0,05$), (rycina 8, tabela 1). Pole powierzchni środka ciężkości dla grupy badanej wyniosło 162,77 mm^2, a dla grupy kontrolnej 96,67 mm^2, różnica nie była istotna statystycznie (tabela 1).

Tabela 1 - Droga i pole powierzchni środka ciężkości

Analizowana zmienna	Grupa badana	Grupa kontrolna	Wartość p
	Średnia ± odchylenie standardowe		
Powierzchnia środka ciężkości [mm^2]	162,77 ± 132,85	96,67 ± 73,89	0,324
Droga środka ciężkości [mm]	1307,31 ± 372,33	896,34 ± 272,89	0,038
* Test t-Student.			



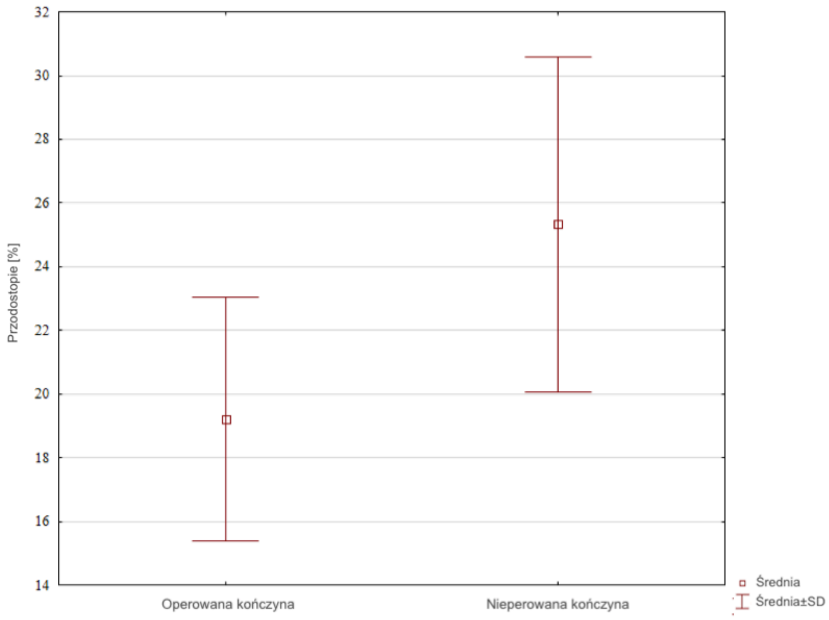
Rycina 8 – Droga środka ciężkości grupy badanej w porównaniu do grupy kontrolnej.

Procentowy rozkład obciążeń między kończyną operowaną, a nieoperowaną wśród grupy badanej oraz między kończyną dominującą, a niedominującą wśród grupy kontrolnej nie ujawniła istotnych statystycznie różnic (tabela 2). Ten sam rezultat uzyskano dla obciążeń tyłostopia pomiędzy kończynami analizowanych grup. W przypadku rozkładu obciążeń przodostopia w grupie badanej uzyskaliśmy istotnie mniejsze wartości dla kończyny operowanej 19,22%, w porównaniu do nieoperowanej 25,33% ($p=0,039$), (tabela 2, rycina 9).

Tabela 2 - Rozkład obciążeń kończyn u pacjentów po operacji w porównaniu z grupą kontrolną.

Rozkład obciążeń kończyn	Grupa kontrolna	Pacjenci po operacji
	Średnia ± odchylenie standardowe	
Kończyna operowana [%]	47,16 ± 2,97	46,01 ± 5,67
Kończyna nieoperowana [%]	52,83 ± 13,72	53,11 ± 7,23
p*	0,715	0,077
Przodostopie OL [%]	23,66 ± 3,7	19,22 ± 4,79
Przodostopie NOL [%]	26,41 ± 4,75	25,33 ± 6,57
p*	0,128	0,039
Tyłostopie OL [%]	23,5 ± 3,06	27,66 ± 6,34
Tyłostopie NOL [%]	26,41 ± 4,81	27,77 ± 4,54
p*	0,090	0,966

OL – kończyna operowana; NOL – kończyna nieoperowana
* Test t-Student.



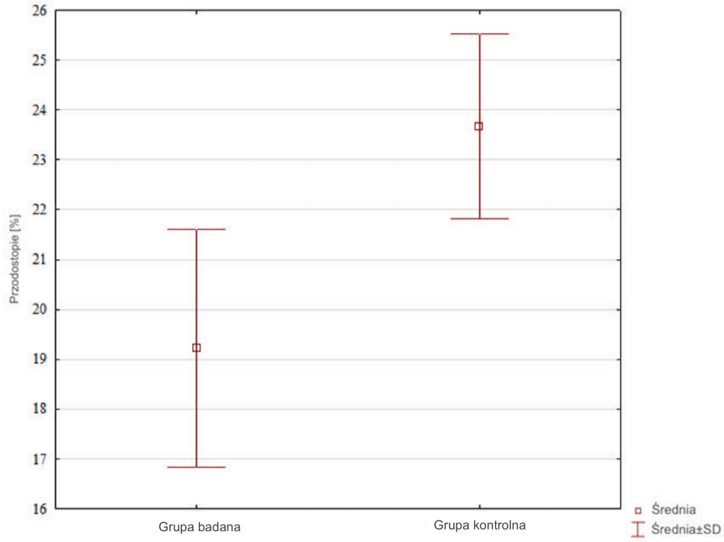
Rycina 9 - Rozkład obciążeń przodostopia pomiędzy operowaną, a zdrową kończyną w grupie badawczej.

W kończynie operowanej pacjentów z grupy badawczej zaobserwowano istotnie mniejsze obciążenie przodostopia (19,22%) w porównaniu z niedominującą kończyną osób z grupy kontrolnej (23,66%), (p=0,026), (tabela 3, rycina 10). Pozostałe analizowane parametry nie były istotnie statystycznie (tabele 2-3).

Tabela 3 – Rozkład obciążeń kończyn w grupie badanej i kontrolnej.

Analizowana zmienna	Grupa badana	Grupa kontrolna	p*
	Średnia ± odchylenie standardowe		
Operowana kończyna [%]	46±5,67	47,16±2,97	0,668
Nieoperowana kończyna [%]	53,11±7,23	48,66±13,72	0,390
Przodostopie OL [%]	19,22±2,79	23,66±2,71	0,026
Tyłostopie OL [%]	27,66±5,34	23,5±3,06	0,060
Przodostopie NOL [%]	25,33±6,57	26,41±4,75	0,666
Tyłostopie NOL [%]	27,77±4,54	26,42±4,81	0,519

OL – kończyna operowana; NOL – kończyna nieoperowana
* Test t-Student.



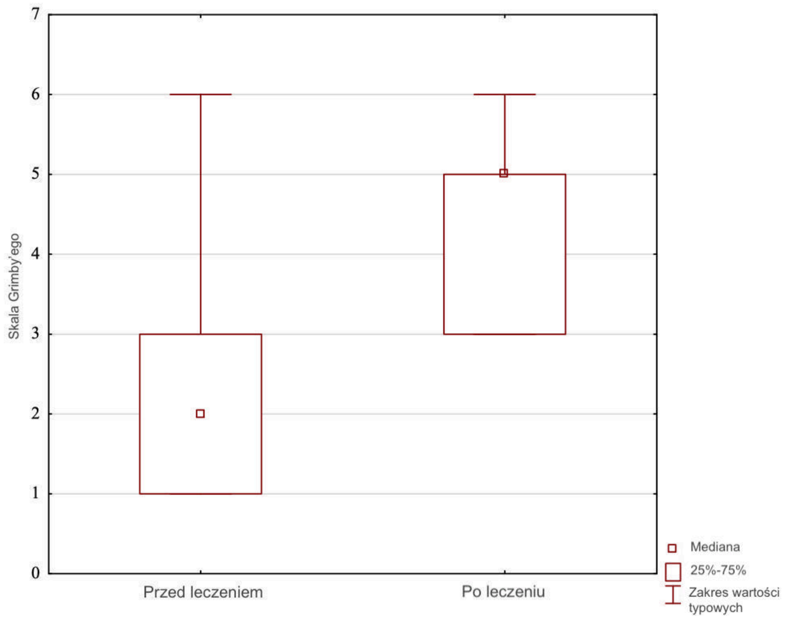
Rycina 10- Porównanie rozkładu obciążeń przodostopia między operowaną kończyną w grupie badawczej, a niedominującą w grupie kontrolnej.

W drugim artykule zaobserwowaliśmy istotą poprawę aktywności w skali UCLA, gdzie średni wynik wzrósł z 2 przed operacją do 5 w okresie obserwacji (Z=1,890, p =0,048), (tabela 4). Średni poziom aktywności fizycznej, oceniany za pomocą skali Grimby'ego, wykazał statystycznie istotny wzrost z 2 przed zabiegiem do poziomu 5 w okresie obserwacyjnym (Z= 2,267, p =0,023), (tabela 4, rycina 11).

Tabela 4- Szczegółowa ocena funkcjonalna pacjentów przed i po operacji

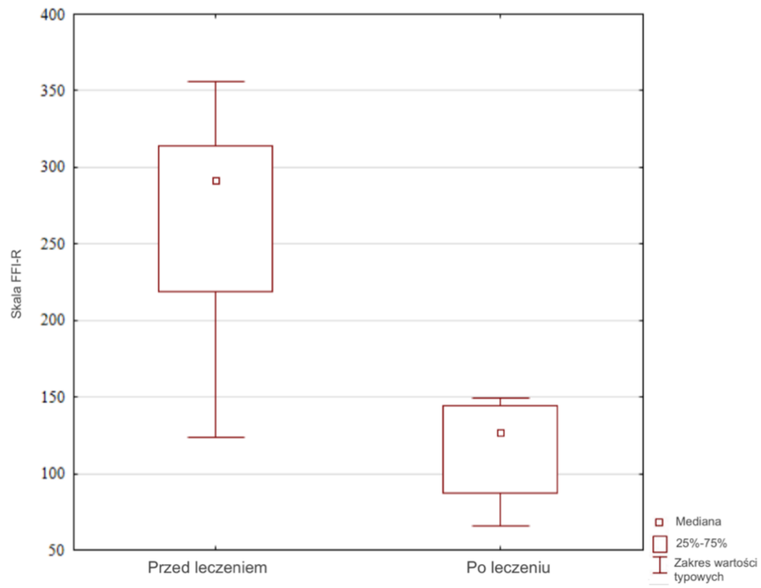
Analizowane zmienne		**Przed leczeniem**	**Po leczeniu**	**p***
		Wartości		
Skala UCLA	Q1	1	4	0.048
	Mediana	2	5	
	Q3	7	6	
Skala Gimbry	Q1	1	3	0.023
	Mediana	2	5	
	Q3	3	5	
Skala aktywności VAS	Q1	0	5	0.723
	Mediana	3	6	
	Q3	8	8	
Skala FFI-R	Q1	219	87	0.013
	Mediana	292	127	
	Q3	314	144	

* Test rang Wilcoxona; Q1, Q3 – pierwszy i trzeci kwartyl



Rycina 11- Ocena aktywności przed i po operacji według skali Grimby'ego.

Wzrost aktywności w skali VAS z 3 do 6 nie był istotny statystycznie (Z=0,353, p =0,723), (tabela 4). Na podstawie wyników kwestionariusza FFI-R zaobserwowano istotną statystycznie poprawę, mediana punktacji zmniejszyła się z 292 przedoperacyjnie do 127 pooperacyjnie (Z = 0,244, p = 0,013), (rycina 12, tabela 4).



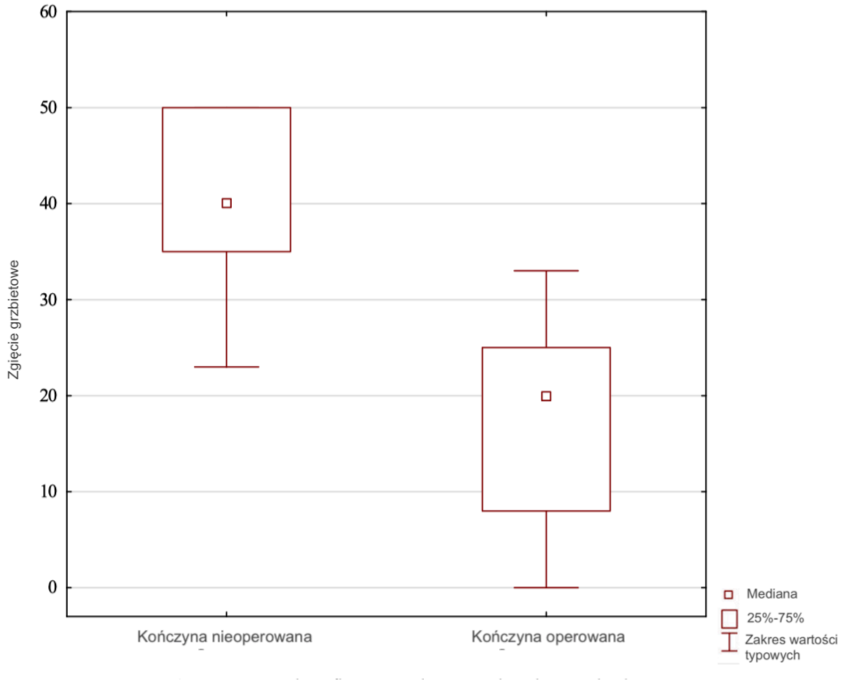
Rycina 12- Wynik oceny funkcjonalnej z zastosowaniem kwestionariusza FFI-R u pacjentów przed i po operacji.

Obserwacja pooperacyjna wykazała statystycznie istotną różnicę w zakresie zgięcia grzbietowego stawu skokowego pomiędzy operowaną kończyną, mediana 20 stopni, a kończyną nieoperowaną, mediana 40 stopni (Z = 2,666, p = 0,007), (tabela 5, rycina 13).

Tabela 5- Zakres ruchomości stawu skokowego w grupie badawczej

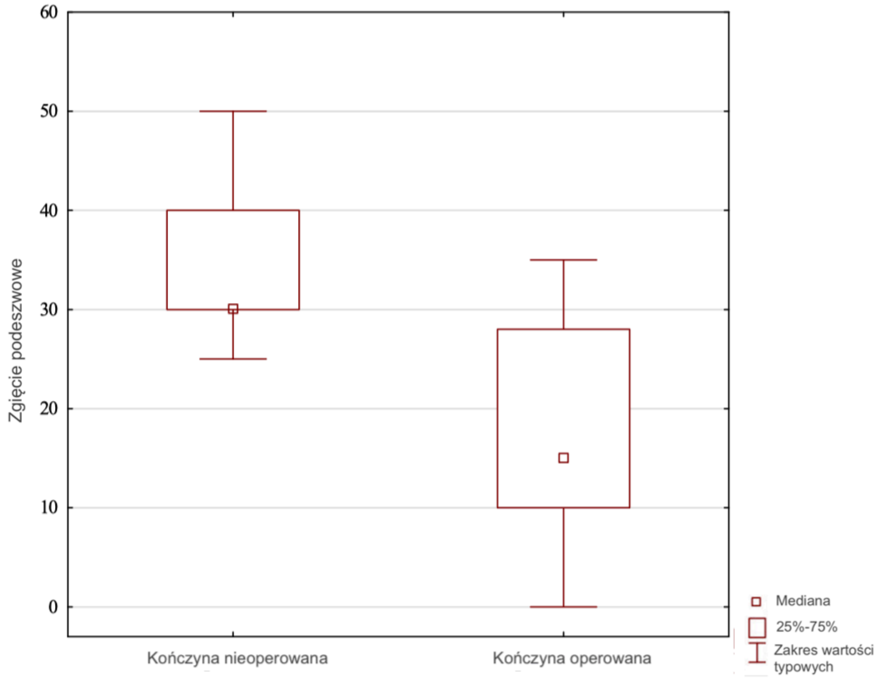
Analizowana zmienna		**Kończyna operowana**	**Kończyna nieoperowana**	**p***
		Wartości		
Zgięcie grzbietowe [°]	Q1	8	35	0.007
	Mediana	20	40	
	Q3	25	50	
Zgięcie podeszwowe [°]	Q1	10	30	0.007
	Mediana	15	30	
	Q3	28	40	
Inwersja [°]	Q1	5	5	0.039
	Mediana	5	15	
	Q3	10	20	
Ewersja [°]	Q1	5	5	0.683
	Mediana	8	15	
	Q3	10	20	

* Test rang Wilcoxona; Q1, Q3 – pierwszy i trzeci kwartyl



Rycina 13 – Porównanie zgięcie grzbietowe stawu skokowego między operowaną, a zdrową kończyną

Zakres zgięcia podeszwowego również był istotnie mniejszy w kończynie operowanej, wynosił 15 stopni, podczas gdy w kończynie nieoperowanej osiągał 30 stopni (Z=1,874, p=0,007), (tabela 5, rycina 14).



Rycina 14 - Porównanie zgięcia podeszwowego stawu skokowego między operowaną, a zdrową kończyną

Mediana zakresu inwersji w stawie skokowym wynosiła 5 stopni w kończynie operowanej i 15 stopni w kończynie nieoperowanej, była to istotna statystycznie różnica, (Z = 1,741, p = 0,039), (tabela 5). Mediana zakresu ewersji również wykazała różnicę — 8 stopni w kończynie operowanej i 15 stopni w kończynie zdrowej — jednak różnica ta nie była statystycznie istotna (Z = 0,325, p = 0,683), (tabela 5).

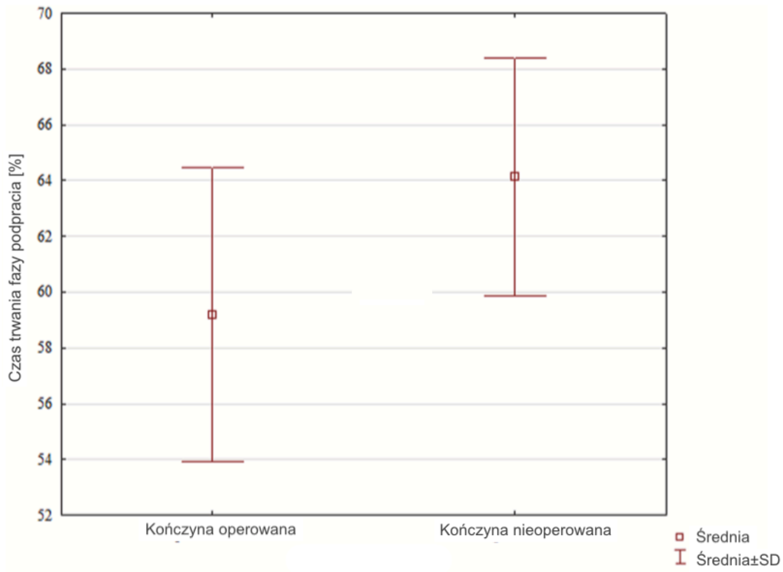
Analiza przedstawiona w trzeciej publikacji nie wykazała istotnych statystycznie odchyleń w parametrach chodu, takich jak kadencja, prędkość, długość kroku pomiędzy grupą pacjentów a grupą kontrolną (tabela 6). Faza podporu w kończynie leczonej była istotnie skrócona (59%) w porównaniu do kończyny zdrowej (64%; p = 0,043) (tabela 7, rycina 15). Również faza pojedynczego podparcia była krótsza w kończynie operowanej (36% vs 42%; p = 0,025) (tabela 7, rycina 16). Inne parametry chodu nie różniły się istotnie (tabela 7).

Tabela 6 – Wybrane parametry chodu grupy badawczej i kontrolnej

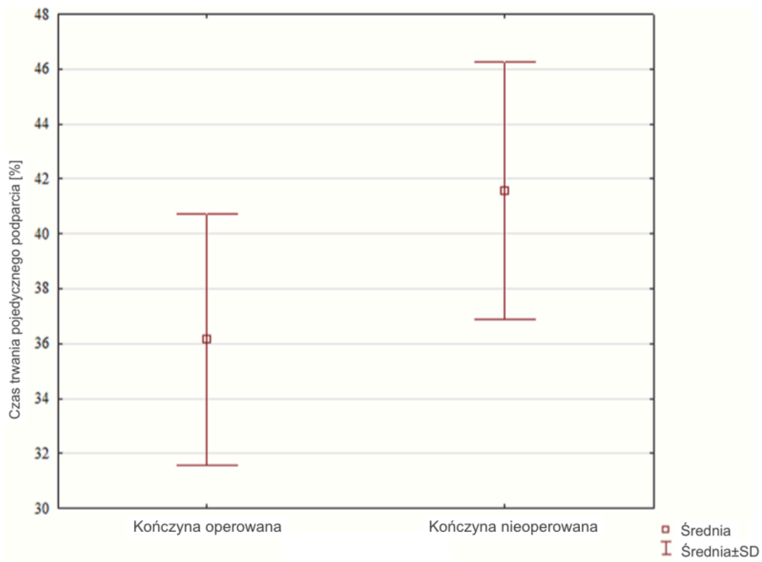
Analizowana zmienna	**Grupa pacjentów**		**Wartość p***
	Grupa pacjentów	**Grupa kontrolna**	
	(średnia ± odchylenie standardowe)		
Czas analizy (s)	67,03 ± 26,17	53 ± 33,77	0,315
Kadencja (kroki/min)	97,28 ± 8,28	90,81 ± 13,01	0,209
Prędkość (m/s)	1,02 ± 0,26	0,83 ± 0,21	0,075
Długość kroku (m)	0,63 ± 0,12	0,54 ± 0,07	0,055
*Test t-Student			

Tabela 7 – Parametry czasoprzestrzenne chodu u pacjentów po zabiegu operacyjnym

Analizowana zmienna	**OL**	**NOL**	**Wartość p***
	(średnia ± odchylenie standardowe)		
Czas trwania cyklu chodu (s)	1,27 ± 0,08	1,26 ± 0,07	0,76
Długość kroku (%)	50,95 ± 3,42	49,04 ± 3,42	0,254
Czas trwania fazy podporu (%)	59,18 ± 5,27	64,13 ± 4,24	0,043
Czas trwania fazy przenoszenia (%)	40,81 ± 5,27	36,07 ± 4,56	0,058
Czas trwania podwójnego podporu (%)	11,81 ± 2,61	10,74 ± 2,83	0,416
Czas trwania pojedynczego podporu (%)	36,14 ± 4,58	41,57 ± 4,71	0,025
Liczba analizowanych kroków	14,11 ± 8,97	13,77 ± 7,49	0,933
OL – kończyna operowana; NOL – kończyna nieoperowana * Test t-Student.			



Rycina 15 – Czas trwania fazy podparcia kończyny operowanej i nieoperowanej u pacjentów po operacji.



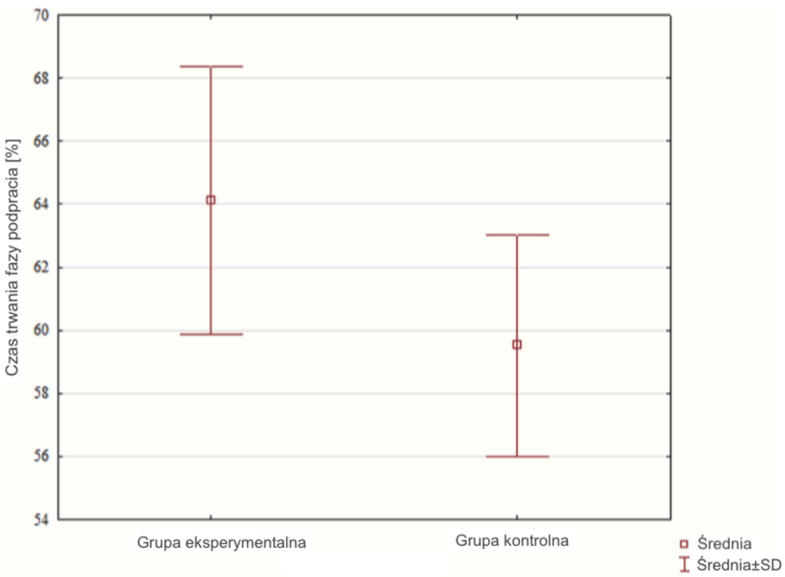
Rycina 16 - Czas trwania fazy pojedynczego podparcia kończyny operowanej i nieoperowanej u pacjentów po operacji

Pomiędzy grupami wykazano różnice jedynie w dwóch parametrach: faza podporu kończyny nieoperowanej w grupie badanej była dłuższa (64% vs 60%; p = 0,013), natomiast faza przenoszenia krótsza (36% vs 40%; p = 0,02) (tabela 8, ryciny 17 i 18).

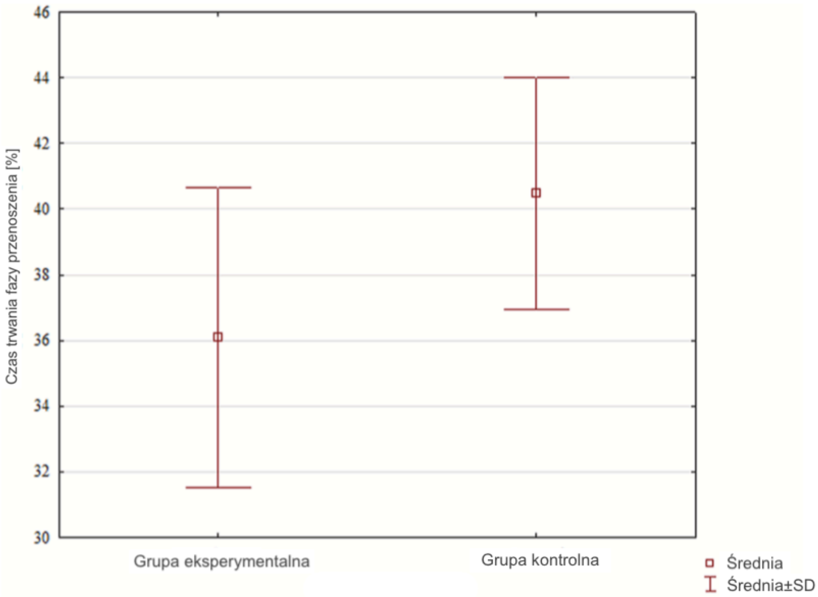
Tabela 8- Szczegółowe parametry chodu u pacjentów i grupy kontrolnej

Analizowana zmienna	Pacjenci	Grupa kontrolna	Wartość p*
	(średnia ± odchylenie standardowe)		
Czas trwania cyklu chodu OL (s)	1.27±0.08	1.37±0.23	0.238
Długość kroku OL (%)	50.95±3.42	48.61±3.29	0.129
Czas trwania fazy podporu OL (%)	59.18±5.27	61.68±2.71	0.171
Czas trwania fazy przenoszenia OL (%)	40.81±5.27	38.31±2.71	0.171
Czas trwania podwójnego podporu OL (%)	11.81±2.61	10.48±2.64	0.264
Czas trwania pojedynczego podporu OL (%)	36.14±4.58	39.39±3.71	0.088
Liczba analizowanych kroków OL	14.11±8.97	11.83±10.07	0.598
Czas trwania cyklu chodu NOL (s)	1.26±0.07	1.39±0.23	0.146
Długość kroku NOL (%)	49.04±3.42	51.39±3.29	0.129
Czas trwania fazy podporu NOL (%)	64.13±4.24	59.51±3.52	0.013
Czas trwania fazy przenoszenia NOL (%)	36.07±4.56	40.49±3.52	0.021
Czas trwania podwójnego podporu NOL (%)	10.74±2.83	11.39±2.39	0.576
Czas trwania pojedynczego podporu NOL (%)	41.57±4.71	38.24±2.64	0.053
Liczba analizowanych kroków NOL	13.77±7.49	10.83±8.27	0.411

OL – kończyna operowana; NOL – kończyna nieoperowana
* Test t-Student.



Rycina 17 - Czas trwania fazy podparcia kończyny nieoperowanej w grupie eksperymentalnej i kończyny dominującej w grupie kontrolnej



Rycina 18 – Czas trwania fazy przenoszenia kończyny nieoperowanej w grupie eksperymentalnej i kończyny dominującej w grupie kontrolnej

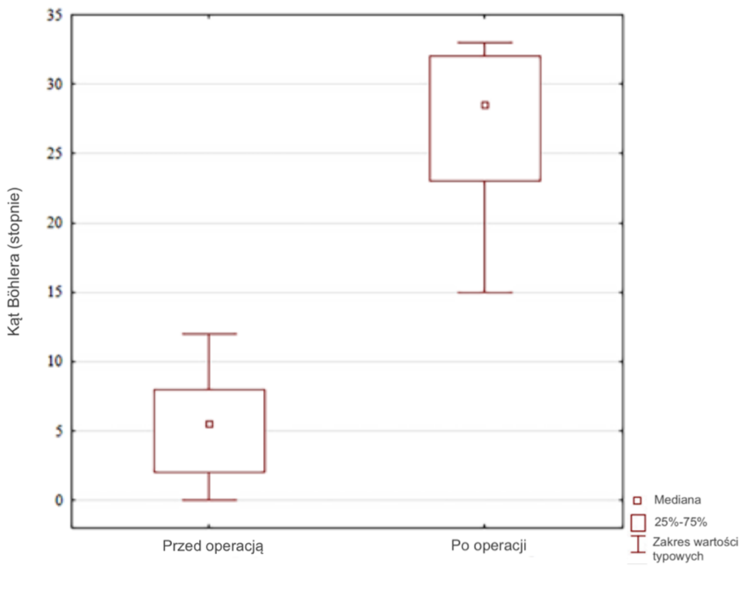
Średni poziom bólu wg VAS w badaniu kontrolnym wynosił 2,3 (0–6). Kąt Böhlera wzrósł z 5,5° do 28,5° (p < 0,001), a kąt Gissane'a z 119° do 143° (p < 0,001).
W ostatniej publikacji średni poziom bólu po zabiegu w skali VAS wynosił 2,3 (0–6). Przed operacją wszyscy pacjenci przyjmowali leki przeciwbólowe, po operacji 2 osoby (7,4%). Z leczenia zadowolonych było łącznie 96% pacjentów (40,7% – zadowolonych, 59,3% – bardzo zadowolonych). Średni wynik AOFAS po leczeniu wynosił 76,6 pkt. Stabilizator Ilizarowa usuwano średnio po 88 dniach, hospitalizacja trwała średnio 7,4 dnia, a operacja trwała średnio 44 minuty. Wszyscy pacjenci zadeklarowali, że ponownie wybraliby tę samą metodę leczenia. Odnotowano jedynie powierzchowne zakażenia w miejscu wprowadzenia drutów Kirschnera (5 pacjentów, 18,5%), skutecznie leczone antybiotykami doustnymi. Nie stwierdzono żadnych poważnych powikłań, takich jak martwica, głębokich zakażeń, reoperacje czy uszkodzeń nerwów. W odległej kontroli zmiany zwyrodnieniowe stwierdzono w stawie skokowo-piętowym u 8 pacjentów, nie odnotowano zmian zwyrodnieniowych w innych ocenianych stawach. Istotnie poprawiły się parametry radiologiczne: kąt Böhlera wzrósł z 5,5° do 28,5° (Z= -4,461, p<0,001) (tabela 9 i 10, rycina 19), kąt infleksji zmniejszył się z 160° do 145° (-3,910, p<0,001) (tabela 9 i 10, rycina 20), a kąt Gissane'a wzrósł z 119° do 143° (Z=-4,382, p<0,001) (tabela 9 i 10, rycina 21).

Tabela 9 – Szczegółowe wyniki radiologiczne przed operacją i podczas ostatniej wizyty kontrolnej

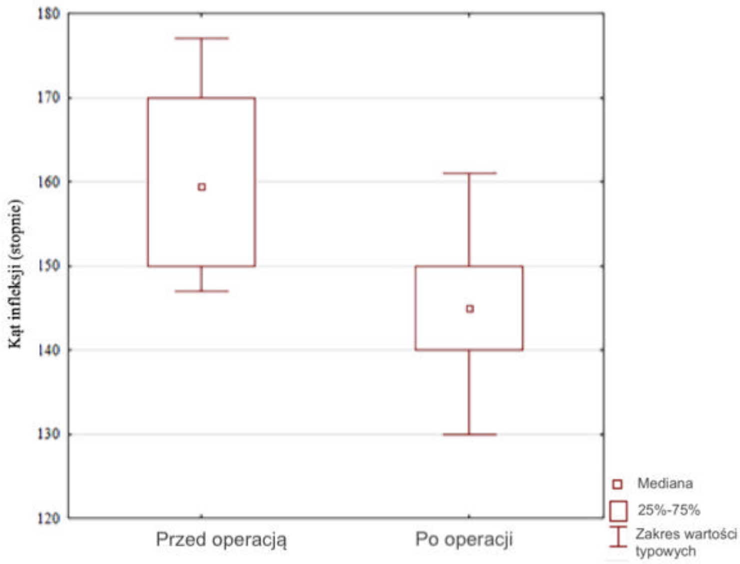
Analizowana zmienna		**Przed leczeniem**	**Ostatnia kontrola**	**Wartość p***
		wartości		
Kąt Böhlera [°]	Q1	2	23	<0.001
	Mediana	5,5	28,5	
	Q3	8	32	
Kąt Gissane'a [°]	Q1	113	137	<0.001
	Mediana	119	143	
	Q3	131	157	
Kąt infleksji [°]	Q1	150	140	<0.001
	Mediana	160	145	
	Q3	170	150	

Tabela 10 - Wyniki sprawdzania normalności rozkładu danych (test Shapiro–Wilka) dla różnic w wartościach zmiennych przed i po operacji przedstawionych na rys. 4–6.

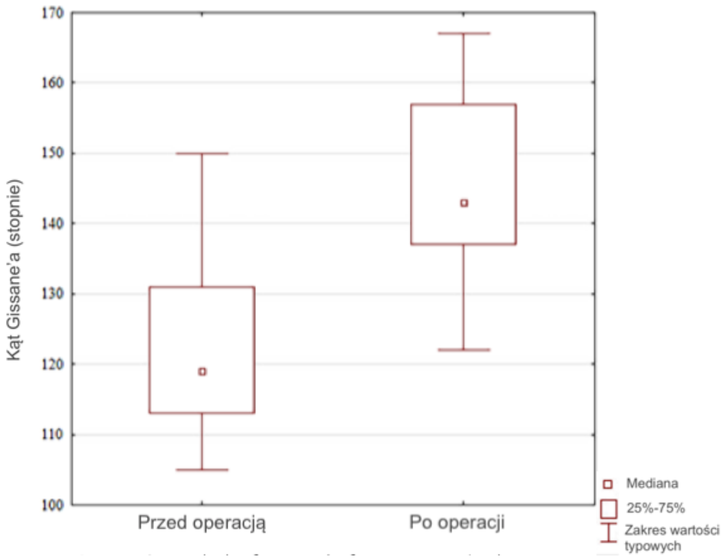
Analizowana zmienna	**W**	**Wartość p**
Kąt Böhlera [°]	0,835	0,010
Kąt Gissane'a [°]	0,856	0,033
Kąt infleksji [°]	0,840	0,014
W – wartość statystyki testowej		



Rycina 19 –Kąta Böhlera przed operacją i po operacji.



Rycina 20 – Kąt infleksji przed operacją i po operacji.



Rycina 21 - Kąt Gissane'a przed operacją i po operacji.

5. Podsumowanie dyskusji

Złamania wewnątrzstawowe kości piętowej stanowią szczególne wyzwanie terapeutyczne dla ortopedów ze względu na ich złożony charakter i wysokie ryzyko powikłań [I/1–4,6,7,9–13,22,33,34; II/5,7,8,11–13]]. W leczeniu tego typu uszkodzeń wykorzystuje się między innymi metodę Ilizarowa [I/2–14]. Zastosowanie zmodyfikowanej polskiej metody Ilizarowa, polegającej na zamkniętej repozycji złamania i stabilizacji przy pomocy zewnętrznego stabilizatora z jedynie jednym drutem Kirschnera w kości piętowej, stanowi innowacyjną alternatywę dla klasycznych metod chirurgicznych [I/4,II/8, III/9., IV/4,15]. Metoda Ilizarowa, będąca techniką mniej inwazyjną w porównaniu do tradycyjnych procedur chirurgicznych, takich jak otwarta repozycja z wewnętrzną stabilizacją za pomocą płyty lub śrub, może skutecznie normalizować parametry równowagi oraz rozkładu obciążeń kończyn dolnych. Jej zastosowanie wiąże się także z istotnie mniejszym ryzykiem powikłań pooperacyjnych [I/1–4,6,7,9–13, IV/2–4,6–9,12–14,18–20]. W szczególności infekcji powierzchownych i głębokich, a także zredukowanym ryzykiem opóźnionego gojenia się ran, martwicy skóry i tkanek podskórnych, które są częstym problemem przy bardziej inwazyjnych technikach operacyjnych [IV/ 2–4,6–9,12–14,18–20].

Głównym celem operacyjnego leczenia złamań kości piętowej jest przywrócenie prawidłowej funkcji stopy, złagodzenie bólu oraz odtworzenie anatomicznego kształtu kości piętowej [I/1,2,4–7,22]. Niektórzy badacze podkreślają, że prawidłowa odbudowa architektury stopy może być kluczowa dla zachowania funkcji stawu skokowego [I/ 1,2,4,6; II/5,6,11,12]. Inne obserwacje pokazują jednak, że zadowalające wyniki funkcjonalne mogą wystąpić mimo deformacji, a niepowodzenia – mimo anatomicznej repozycji odłamów kości piętowej [I/ 2,7; II/6,11,13; III/5,8]. Ograniczenia ruchomości i zaburzenia funkcji stawu skokowego mogą prowadzić do długotrwałej niepełnosprawności [II/2,3,6,8]. W badaniu oceniano równowagę, rozkład masy ciała na kończyny dolne, parametry chodu, funkcję stopy i aktywność fizyczną, zakres ruchomości stawu skokowego oraz wyniki kliniczne i radiologiczne. Wyniki badania wskazują, że leczenie złamań kości piętowej przy użyciu polskiej modyfikacji metody Ilizarowa pozwala na przywrócenie symetrycznego rozkładu obciążenia kończyn dolnych i jest porównywalne do obserwacji innych autorów, którzy również nie stwierdzili istotnych różnic w rozkładzie obciążenia u pacjentów leczonych metodą Ilizarowa w przypadkach leczenia stawu rzekomego piszczeli [I/15,18], kortykotomii [I/16] czy artrodezy stawu skokowego [I/17]. Jednakże, podobnie jak w badaniach Rongiesa [I/19] czy autorów analizujących wyniki po artrodezie stawu skokowego [I/17], parametry równowagi nie uległy całkowitej normalizacji. U naszych pacjentów odnotowano istotnie większe przemieszczenie środka ciężkości, co może świadczyć o niepełnym powrocie do fizjologicznej kontroli posturalnej. Podobne zaburzenia biomechaniki obserwowano również u pacjentów po leczeniu innymi metodami, po stabilizacji płytą złamań kości piętowej [I/22–25,33,34], po leczeniu złamań kości udowej [I/31] i urazach stawu Lisfranca [I/32]. U naszych pacjentów zaobserwowano istotną poprawę poziomu aktywności fizycznej mierzoną za pomocą skal UCLA i Grimby'ego, a także poprawę funkcji ocenianą kwestionariuszem FFI-R, co jest zgodne z wynikami innych badań [II/ 31,32]. Zakres ruchu w stawie skokowym – w szczególności zgięcia grzbietowego, podeszwowego oraz inwersji – był mniejszy w kończynie operowanej w porównaniu do kończyny zdrowej, co potwierdza wcześniejsze obserwacje ograniczonej ruchomości stawów po leczeniu operacyjnym złamań pięty [II/18,19]. Mimo ograniczeń ruchomości, odnotowano poprawę wyników funkcjonalnych, co może być związane z możliwością wczesnego obciążania kończyny oraz mało inwazyjnym charakterem zastosowanej metody [II/3,5,8]. Uzyskane wartości wskaźnika FFI-R były porównywalne do wyników uzyskanych przez innych autorów stosujących zarówno leczenie operacyjne (ORIF), jak i zachowawcze [II/14,19–23]. Obserwowane ograniczenia zakresu ruchu mogą być wynikiem zbyt krótkiej lub niedostatecznej rehabilitacji, tworzenia się zrostów i zwłóknień, utrzymującego się obrzęku oraz zaników mięśniowych [II/7]. Większość parametrów chodu po leczeniu wskazywała normalizację, bez istotnych różnic w kadencji, prędkości chodu i długości kroku w porównaniu z grupą kontrolną zdrowych ochotników. Jedynie faza podporu i faza pojedynczego podporu były krótsze w kończynie operowanej względem kończyny zdrowej, co może wynikać z ograniczonej ruchomości stawu oraz wtórnych zmian zwyrodnieniowych [III/12,15,17,18]. Wyniki badania są zgodne z wcześniejszymi doniesieniami dotyczącymi leczenia metodą ORIF, w których odnotowywano ograniczenia ruchomości, zmniejszenie sił reakcji podłoża oraz asymetrię w obciążeniu kończyn [III/2,15–18]. W porównaniu z nimi, metoda Ilizarowa wykazała porównywalną lub lepszą funkcjonalność kończyny leczonej, bez istotnych różnic względem kończyny niedominującej zdrowych osób. Muir i współpracownicy w przeglądzie systematycznym dotyczącym leczenia złamań kości piętowej z użyciem zewnętrznych stabilizatorów wykazali utrzymujący się ból u 36,7% pacjentów [IV/2]. W moim badaniu średnie pooperacyjne natężenie bólu w skali VAS wynosiło 2,3, co stanowi dobry wynik. Średnia wartość punktowa w skali AOFAS wyniosła 76,6, co jest porównywalne z wynikami uzyskanymi w poprzednich badaniach: 66 u McGarvey [IV/3], 88,2 u Emary [IV/6], 68 u Alego [IV/9], 80 u Li i Mauffreya [IV/10,13], a także 77,5 w przeglądzie systematycznym przeprowadzonym przez Muira [IV/2]. Warto podkreślić, że wszyscy pacjenci zadeklarowali gotowość do ponownego wyboru tej samej metody. Dodatkowo, jedynie 7,4% pacjentów zgłaszało potrzebę stosowania leków przeciwbólowych podczas odległej kontroli, w przeciwieństwie do okresu przedoperacyjnego, kiedy to środki przeciwbólowe stosowali wszyscy uczestnicy badania. Czas utrzymania stabilizatora wynosił średnio 88 dni, czas hospitalizacji był krótszy (średnio 7,4 dnia) niż w innych badaniach [IV/4], a sama operacja trwała średnio 44 minuty. W odróżnieniu od wcześniejszych prac, w których powikłania pojawiały się u 20%–66% pacjentów [IV/2,3,6,10,12], w omawianym badaniu wystąpiły one tylko u 18,5% i były ograniczone do powierzchownych infekcji miejsca wprowadzenia drutów Kirschnera. Nie odnotowano konieczności reoperacji ani poważniejszych powikłań. Zmiany zwyrodnieniowe pojawiły się jedynie w stawie podskokowym u 29,6% pacjentów, co jest mniejszym odsetkiem niż w badaniach Alego (44% w stawie podskokowym, 24% w piętowo-sześciennym) [9] oraz niż ogólny przedział 44%–68% podany w literaturze [IV/2,9]. Parametry radiologiczne, takie jak kąt Böhlera (wzrost z 5,5° do 28,5°), kąt infleksji (spadek ze 160° do 145°) i kąt Gissane'a (wzrost ze 119° do 143°), uległy istotnej poprawie, co jest zgodne z innymi doniesieniami [IV/1,2,4,9,10,13].

6. Wnioski

1. Zastosowanie polskiej modyfikacji metody Ilizarowa w leczeniu wewnątrzstawowych złamań kości piętowej przynosi dobre efekty kliniczne, funkcjonalne i biomechaniczne.

2. Metoda ta umożliwia skuteczną repozycję odłamów i stabilizację złamania przy jednoczesnym ograniczeniu ryzyka powikłań związanych z klasycznymi technikami otwartymi.

3. U większości pacjentów odnotowano powrót do dobrej sprawności i aktywności, mimo umiarkowanego ograniczenia ruchomości w stawie skokowym.

4. Parametry chodu i rozkład obciążeń kończyn u pacjentów po leczeniu był zbliżony do wartości u osób zdrowych. Umożliwia to wczesną mobilizację i szybki powrót do codziennego funkcjonowania, co czyni metodę Ilizarowa wartościową alternatywą w leczeniu wewnątrzstawowych złamań kości piętowej.

7. Piśmiennictwo dotyczące publikacji

7.1. Publikacja I

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8. Streszczenie w języku polskim

Wstęp:

Pomimo rozwoju technik operacyjnych, leczenie wewnątrzstawowych złamań kości piętowej, które stanowią 75% wszystkich złamań w obrębie kości piętowej nadal budzą kontrowersje ze względu na duże ryzyko powikłań oraz niejednoznaczne wyniki funkcjonalne. Polska modyfikacja metody Ilizarowa stanowi innowacyjne podejście, pozwalające na stabilizację złamania bez otwartej repozycji i z wykorzystaniem jedynie jednego drutu Kirschnera wprowadzanego w kość piętową. Praca stanowi analizę skuteczności tej metody, obejmującej ocenę kliniczną, radiologiczną oraz biomechaniczną, z uwzględnieniem rozkładu obciążenia kończyn dolnych oraz funkcji stawu skokowego. Do tej pory brakowało doniesień naukowych analizujących efekty leczenia złamań kości piętowej z wykorzystaniem polskiej modyfikacji metody Ilizarowa.

Cele pracy:

Kompleksowa ocena kliniczna, biomechaniczna, funkcjonalna i radiologiczna pacjentów po leczeniu złamań kości piętowej polską modyfikacją metody Ilizarowa. Retrospektywna analiza chodu u pacjentów po leczeniu operacyjnym złamań wewątrzstawowych kości piętowej.

Materiały i Metody:

Analizie poddano dane z czterech retrospektywnych badań prowadzonych w latach 2021–2022, dotyczących leczenia wewnątrzstawowych złamań kości piętowej z zastosowaniem polskiej modyfikacji metody Ilizarowa. W trzech analizach oceniano łącznie 21 pacjentów (7 kobiet, 14 mężczyzn), natomiast w ocenie kliniczno-radiologicznej wzięło udział 27 pacjentów (2 kobiety, 25 mężczyzn). Do kryteriów włączenia należały: leczenie polską modyfikacją stabilizatora Ilizarowa, minimum dwuletni okres obserwacji, brak współistniejących chorób kończyn dolnych, kompletna dokumentacja kliniczna, radiologiczna i funkcjonalna oraz świadoma zgoda pacjenta. Repozycja złamania odbywała się na zamknięto, a stabilizator składał się z dwóch pierścieni mocowanych do podudzia oraz półpierścienia mocowanego do kości piętowej jednym drutem Kirschnera. Ocenie poddano: funkcję stopy (FFI-R), aktywność fizyczną (skale UCLA, Grimby'ego, VAS), zakresy ruchomości stawu skokowego (zgięcie grzbietowe, podeszwowe, inwersja, ewersja), parametry chodu (kadencja, prędkość, długość kroku, fazy podporu i przenoszenia – czujnik BTS G-SENSOR), statyczną równowagę i rozkład obciążeń kończyn dolnych (platforma pedobarograficzna FreeMED MAXI), a także parametry radiologiczne (kąt Böhlera, kąt Gissane'a, kąt infleksji). Grupę badaną porównywano z grupą kontrolną 19–21 zdrowych ochotników, dopasowaną pod względem płci i wskaźnika BMI.

Wyniki:

U pacjentów zaobserwowano istotnie dłuższą drogę środka ciężkości (1307,31 mm) w porównaniu do grupy kontrolnej (896,34 mm; p = 0,038), przy braku różnic w powierzchni środka ciężkości (p = 0,324). Procentowy rozkład obciążenia kończyn był symetryczny, natomiast istotnie niższe obciążenie przodostopia stwierdzono w kończynie operowanej (19,22 %) względem nieoperowanej (25,33 %; p = 0,039) oraz kończyny niedominującej w grupie kontrolnej (23,66 %; p = 0,026). Po leczeniu odnotowano istotną poprawę aktywności: skala UCLA wzrosła z 2 do 5 (p = 0,048), Grimby'ego z 2 do 5 (p = 0,023), a wynik FFI-R zmniejszył się z 292 do 127 punktów (p = 0,013). Ruchomość stawu skokowego w kończynie operowanej była ograniczona: zgięcie grzbietowe 20° vs 40° (p = 0,007), podeszwowe 15° vs 30° (p = 0,007), inwersja 5° vs 15° (p = 0,039). W analizie chodu faza podparcia była krótsza w kończynie operowanej (59% vs 64%; p = 0,043), podobnie jak faza pojedynczego podparcia (36% vs 42%; p = 0,025). Ponadto faza przenoszenia zdrowej kończyny pacjentów po operacji była skrócona i wynosiła 36% vs 40% w kończynie dominującej grupy kontrolnej (*p* = 0,02). Ból oceniany w skali VAS wynosił średnio 2,3 (0–6), a 96% pacjentów było zadowolonych z leczenia. Istotnie poprawiły się parametry radiologiczne: kąt Böhlera wzrósł z 5,5° do 28,5°, kąt Gissane'a z 119° do 143°, a kąt infleksji zmniejszył się z 160° do 145° (wszystkie p < 0,001). Odsetek powikłań był niski (18,5%) i ograniczał się do powierzchownych infekcji przy drutach Kirschnera.

Dyskusja:

Złamania wewnątrzstawowe kości piętowej stanowią poważne wyzwanie terapeutyczne ze względu na złożoną anatomię i wysokie ryzyko powikłań. Zastosowanie polskiej modyfikacji metody Ilizarowa, opartej na zamkniętej repozycji i stabilizacji zewnętrznej z użyciem pojedynczego drutu Kirschnera, stanowi małoinwazyjną alternatywę dla klasycznych technik operacyjnych. Metoda ta pozwala na odtworzenie anatomii kości piętowej oraz przywrócenie równowagi i symetrycznego rozkładu obciążeń kończyn dolnych, przy jednocześnie ograniczonym ryzyku powikłań, takich jak infekcje czy martwica tkanek miękkich.

W badaniu wykazano poprawę parametrów radiologicznych, w tym kątów Böhlera i Gissane'a, oraz zmniejszenie dolegliwości bólowych. Zmniejszenie natężenia bólu, ograniczona potrzeba stosowania leków przeciwbólowych oraz deklarowana przez pacjentów gotowość do ponownego wyboru tej samej metody świadczą o wysokim poziomie satysfakcji z leczenia. U większości pacjentów odnotowano poprawę funkcji kończyny, wzrost poziomu aktywności fizycznej oraz normalizację parametrów chodu. Choć obserwowano pewne ograniczenia ruchomości stawu skokowego i niepełną normalizację kontroli posturalnej, to nie wpłynęły one istotnie na ogólne wyniki funkcjonalne. Metoda Ilizarowa, dzięki niskiemu odsetkowi powikłań, krótszemu czasowi hospitalizacji i możliwości wczesnego obciążania kończyny, może być skuteczną, bezpieczną i klinicznie uzasadnioną metodą leczenia śródstawowych złamań kości piętowej.

Wnioski:

Polska modyfikacja metody Ilizarowa stanowi skuteczną i bezpieczną opcję leczenia wewnątrzstawowych złamań kości piętowej. Umożliwia precyzyjną repozycję odłamów oraz stabilizację złamania przy jednoczesnym ograniczeniu ryzyka powikłań związanych z metodami otwartymi. U większości pacjentów obserwuje się powrót do dobrej sprawności funkcjonalnej, a parametry chodu i rozkład obciążeń kończyn są zbliżone do wartości obserwowanych u osób zdrowych. Uzyskane wyniki, potwierdzają zasadność zastosowania metody Ilizarowa jako efektywnej i bezpiecznej alternatywy w leczeniu wewnątrzstawowych złamań kości piętowej.

9. ABSTRACT PO ANGIELSKU

Introduction:

Despite advances in surgical techniques, the treatment of intra-articular calcaneal fractures—which constitute approximately 75% of all calcaneal fractures—remains controversial due to the high risk of complications and ambiguous functional outcomes. The Polish modification of the Ilizarov method offers an innovative approach that enables fracture stabilization without open reduction, utilizing only a single Kirschner wire inserted into the calcaneus. This study presents an analysis of the effectiveness of this method, including clinical, radiological, and biomechanical assessments, with particular attention to lower limb load distribution and ankle joint function. To date, there has been a lack of scientific reports analyzing the outcomes of calcaneal fracture treatment using the Polish modification of the Ilizarov method.

Objectives:

A comprehensive clinical, biomechanical, functional, and radiological assessment of patients treated for calcaneal fractures using the Polish modification of the Ilizarov technique. A retrospective gait analysis of patients who underwent surgical treatment for intra-articular calcaneal fractures.

Materials and Methods:

The data for our retrospective study came from patients with intra-articular calcaneal fractures treated with the Polish modification of the Ilizarov method in the period between 2021 and 2022.. Three studies included 21 patients (7 women, 14 men), while the clinical and radiological assessment covered 27 patients (2 women, 25 men). Inclusion criteria were: treatment using the Polish Ilizarov stabilizer modification, a minimum follow-up of two years, other lower-limb injuries, lower-limb comorbiditie, complete clinical, radiological, and functional documentation, and informed patient consent. Fracture reduction was performed in a closed manner, and the stabilizer consisted of two rings fixed to the lower leg and a half-ring attached to the calcaneus using a single Kirschner wire. The following parameters were assessed: foot function (FFI-R), physical activity (UCLA, Grimby, VAS scales), ankle joint range of motion (dorsiflexion, plantarflexion, inversion, eversion), gait parameters (cadence, speed, step length, stance and swing phases – BTS G-SENSOR), static balance and lower limb wieght distribution (FreeMED MAXI pedobarographic platform), and radiological

parameters (Böhler's angle, Gissane's angle, inflection angle). The study group was compared with a control group of 19–21 healthy volunteers matched for sex and BMI.

Results:

Patients showed a significantly longer path of the center of gravity (1307.31 mm) compared to the control group (896.34 mm; p = 0.038), with no differences in the area od center od gravity (p = 0.324). The percentage weight distribution between limbs was symmetrical; however, significantly lower forefoot loading was observed in the operated limb (19.22%) compared to the non-operated limb (25.33%; p = 0.039) and the non-dominant limb in the control group (23.66%; p = 0.026). Post-treatment, significant improvements in activity levels were recorded: the UCLA scale increased from 2 to 5 (p = 0.048), Grimby from 2 to 5 (p = 0.023), and the FFI-R score decreased from 292 to 127 points (p = 0.013). Ankle range of motion in the operated limb was limited: dorsiflexion 20° vs. 40° (p = 0.007), plantarflexion 15° vs. 30° (p = 0.007), inversion 5° vs. 15° (p = 0.039). Gait analysis revealed a shorter stance phase in the operated limb (59% vs. 64%; p = 0.043) and a shorter single-support phase (36% vs. 42%; p = 0.025). Moreover, the swing phase of the healthy limb in post-operative patients was shorter (36% vs. 40% in the dominant limb of the control group; p = 0.02). Pain, as assessed on the VAS scale, averaged 2.3 (range 0–6), and 96% of patients expressed satisfaction with the treatment. Radiological parameters significantly improved: Böhler's angle increased from 5.5° to 28.5°, Gissane's angle from 119° to 143°, and the inflection angle decreased from 160° to 145° (all p < 0.001). The complication rate was low (18.5%) and limited to superficial infections around the Kirschner wires.

Discussion:

Intra-articular calcaneal fractures pose a significant therapeutic challenge due to the complex anatomy and high risk of complications. The use of the Polish modification of the Ilizarov method, based on closed reduction and external fixation with a single Kirschner wire, offers a minimally invasive alternative to conventional surgical techniques. This method enables anatomical restoration of the calcaneus and reestablishment of balance and symmetrical lower limb weight distribution, while minimizing risks such as infection or soft tissue necrosis.
The study demonstrated improvements in radiological parameters, including Böhler's and Gissane's angles, as well as a reduction in pain intensity. Reduced pain levels, decreased need for analgesics, and patients' willingness to choose the same treatment again reflect a high level of satisfaction. Most patients showed improved limb function, increased physical

activity, and normalization of gait parameters. While some limitations in ankle range of motion and incomplete postural control normalization were noted, they did not significantly impact overall functional outcomes. Due to its low complication rate, shorter hospitalization time, and allowance for early limb loading, the Ilizarov method may be considered an effective, safe, and clinically justified treatment option for intra-articular calcaneal fractures.

Conclusions

The Polish modification of the Ilizarov method is an effective and safe treatment option for intra-articular calcaneal fractures. It enables precise fracture reduction and stabilization while minimizing the risks associated with open surgical techniques. Most patients regain good functional capacity, and gait parameters and load distribution closely approximate those of healthy individuals. These findings support the use of the Ilizarov method as a reliable and safe alternative for the treatment of intra-articular calcaneal fractures.

10. PUBLIKACJE JAKO ZAŁĄCZNIKI

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Article

Balance and Weight Distribution over the Lower Limbs Following Calcaneal Fracture Treatment with the Ilizarov Method

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Abstract: Background: The biomechanical outcomes of intra-articular calcaneal fracture treatment have not been fully explored. The purpose of this study was to analyze pedobarographic assessments of balance and body weight distribution over the lower limbs in patients following calcaneal fracture treatment with the Ilizarov method and to compare the results with those of a control group. **Materials and Methods**: The data for our retrospective study came from cases of intra-articular calcaneal fractures treated with the Polish modification of the Ilizarov method in the period between 2021 and 2022. The experimental group (21 patients; 7 women, 14 men) included Sanders classification calcaneal fractures type 2 (n = 3), type 3 (n = 5), and type 4 (n = 13). The control group comprised 21 sex-matched healthy volunteers, with no significant differences from the experimental group in terms of age or BMI. The examination included an assessment of balance and weight distribution over the lower limbs. The device used was a FreeMED MAXI pedobarographic platform (SensorMedica). **Results**: The mean displacement of the center of gravity in the experimental group was significantly higher at 1307.31 mm than in the control group (896.34 mm; p = 0.038). The mean area of the center of gravity was not significantly different between the groups. An analysis of weight distribution over the operated and uninjured limb in the experimental group and the non-dominant and dominant limb, respectively, in the control group revealed no significant differences. We observed no significant differences in the percentage of weight distribution over the lower limbs between the operated limb in the experimental group and the non-dominant limb in the control group, or between the uninjured limb in the experimental group and the dominant limb in the control group. **Conclusions**: The use of the Ilizarov method in calcaneal fracture treatment helps normalize the percentage weight distribution in the lower limbs, with the results comparable with those obtained in the healthy control group. The mean displacement of the center of gravity was worse in the experimental group than in controls; whereas the mean area of the center of gravity was comparable between the two groups. Treatment of calcaneal fractures with the Ilizarov method does not help achieve completely normal static parameters of lower-limb biomechanics. Patients treated for calcaneal fractures with the Ilizarov method require longer and more intense rehabilitation and follow-up.

Keywords: balance; weight distribution; biomechanics; Ilizarov method; intra-articular; calcaneal fractures

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1. Introduction

Fractures of the calcaneus account for approximately 2% of all fractures and for 50–60% of tarsal fractures [1–5]. The intra-articular and comminuted fractures of the calcaneus that require surgical treatment constitute approximately 75% of all calcaneal fractures [1–4]. There is no gold standard for the treatment of intra-articular and comminuted fractures of the calcaneus [1–4,6–13]. In the past, most calcaneal fractures were treated either by closed reduction and cast immobilization or by bone fragment repositioning and fixation with a few Kirschner wires or Steinmann pins [2,6,10]. Technological advancement has popularized the technique of open reduction and internal plate fixation of calcaneal fractures [1–4,6,7]; however, the necessary large incision has been associated with a high risk of complications, including delayed wound healing, infections, skin and soft tissue necrosis, fixation material-induced irritation, or loss of fixation (14–33%) [1–3,6,7].

One of the techniques used in calcaneal fracture management is the Ilizarov method [2–14]. Due to the high risk of complications and the complexity of the required surgical technique, calcaneal fractures have always posed a challenge for orthopedic surgeons [1–4,6,7,9–13]. Earlier papers on the topic dealt primarily with the clinical [2–7,10,12], radiological [2–5,9,10,13], and functional [2,3,6,9,10,13] outcomes of treating calcaneal fractures with external fixators and the Ilizarov method.

The growing use of various implants (Kirschner wires, Schanz pins) to complement the Ilizarov method may increase the risk of complications, such as peri-implant infections, delayed wound healing, or skin and soft-tissue necrosis [2,4]. The techniques for intra-articular calcaneal fracture management reported to date include the use of the Ilizarov method along with the insertion of at least three Kirschner wires into the foot [2,3,5–9,12–14]. The modified approach to intra-articular calcaneal fractures with the use of an Ilizarov fixator conducted in a center in Wrocław, Poland, requires the insertion of a single Kirschner wire into the foot [4].

The biomechanical outcomes of intra-articular calcaneal fracture treatment have not been fully explored. Such fractures result in bone fragment displacement, which alters the overall shape and three-dimensional structure of the calcaneus and of the whole foot [1,2,4,6]. One of the purposes of surgical treatment in intra-articular calcaneal fractures is to restore the shape and three-dimensional structure of both the calcaneus and the whole foot, in order to normalize kinetic and static parameters of the lower limbs [1,2,4,6]. Any abnormalities in the three-dimensional structure of the calcaneus and foot may lead to asymmetric load distribution in the foot, which causes pain, as well as accelerates tissue degeneration [4]. Post-traumatic deformities and changes in three-dimensional structure of the calcaneus and foot may adversely affect gait, balance, and weight distribution over the lower limbs [1,2,4,6,15–25].

Normal gait function is largely dependent on the anatomical bony structure of the foot [5–7,14]. Apart from the standard clinical and radiological assessments following lower-limb surgery, it is very important to also evaluate biomechanical parameters [15–25]. Pedobarography helps assess balance parameters and the distribution of loads on the lower limbs [15–23,26–37]. Pedobarography is an accepted method for examining the statics and dynamics of musculoskeletal issues [15–34,36]. Pedobarography is a useful, reproducible, objective, and comparable assessment method in the treatment of musculoskeletal pathologies [15–23,26–29,34–36]. Unfortunately, there is a lack of available literature on lower-limb biomechanics assessments following calcaneal fracture treatment with the Ilizarov method. The authors of earlier papers on calcaneal fracture treatment have only assessed gait following an open reduction and internal plate fixation approach [22–25]. The assessed parameters included also the mean contact area, peak pressures in the forefoot and hindfoot, and total contact time in patients with calcaneal fractures treated with an open reduction and internal plate fixation approach [33,34]. There have been no studies to assess the balance and weight distribution over the lower limbs following calcaneal fracture treatment. The studies conducted so far included assessments of balance and weight distribution over the lower limbs following lengthening and corrective corticotomy procedures on the thigh and leg with the Ilizarov method, ankle joint arthrodesis procedures, or tibial nonunion treatment with the Ilizarov method [15–18].

We hypothesized that calcaneal fracture treatment with the Ilizarov method would help restore normal balance and weight distribution over the lower limbs. The purpose of this study was to analyze pedobarographic assessments of balance and body weight distribution over the lower limbs in patients following calcaneal fracture treatment with the Ilizarov method and to compare the results with those of a control group of healthy individuals.

2. Materials and Methods

The data for our retrospective study came from patients with intra-articular calcaneal fractures treated with the Polish modification of the Ilizarov method in the period between 2021 and 2022. The study inclusion criteria were as follows: intra-articular calcaneal fracture treated with the Polish modification of the Ilizarov method, a follow-up period of over 2 years after treatment completion, complete medical and radiological records, complete pedobarographic assessment records, patient's written informed consent, and the absence of lower-limb comorbidities. The study exclusion criteria were as follows: calcaneal fracture treatment with a method different than the Ilizarov method, a follow-up period of less than 2 years, incomplete medical and/or radiographic records, incomplete pedobarographic assessment records, other lower-limb injuries, lower-limb comorbidities, and a lack of consent. All patients were informed of the voluntary nature of study participation and the possibility of withdrawing from the study at any time. This study was approved by the local ethics committee (UO/0023/KB/2023).

Application of the inclusion and exclusion criteria yielded 21 patients (7 women, 14 men), aged from 25 to 67 years (mean age 47 years), with a body mass index of 24–40 (mean 28), height of 152–188 cm (mean 171 cm), body weight of 61–130 kg (mean 81 kg). The control group comprised 21 sex-matched healthy volunteers, with no significant differences from the experimental group in terms of age, demographics, BMI, or physical activity levels.

The experimental group included Sanders classification calcaneal fractures type 2 ($n = 3$), type 3 ($n = 5$), and type 4 ($n = 13$). Each of the evaluated patients was operated on by the same surgeon, who used the Polish modification of the Ilizarov method for calcaneal fracture treatment [4] (verbal accounts by P. Koprowski and L. Morasiewicz).

The external fixator used for calcaneal fracture treatment in accordance with the Polish modification of the Ilizarov method was composed of two fully circular rings, which were fixed to crural bones with Kirschner wires, and one half-ring, which was fixed to the calcaneus with a single Kirschner wire (Figure 1).

All surgical procedures were conducted with a closed approach, without an open access to the calcaneus. Once the two full rings were mounted on the leg, one Kirschner wire was inserted (under fluoroscopy) into the calcaneal bone fragment that was both the most proximal and the most dorsal. Subsequently, the half-ring was positioned behind the foot and fixed to a Kirschner wire inserted into the calcaneus. The half-ring was then connected with the distal leg ring by means of two connectors (Figure 2).

Each connector was composed of two perpendicular, threaded rods (Figure 2). Once the fixator was mounted on the leg and foot, the calcaneal fracture was reduced under fluoroscopy. Ligamentotaxis via this modified Ilizarov fixator allowed a closed, indirect reduction in the calcaneal fracture. On day one after surgery, the patients began walking with two elbow crutches, with partial weight bearing on the treated limb. Gradually, the patients were allowed to bear more and more weight on the operated foot, to the extent of their pain tolerance. All patients underwent the same rehabilitation protocol and were scheduled for periodic follow-up visits in an outpatient setting. The follow-up visits included clinical examination and radiological imaging. The fixator was removed once clinical and radiological evidence of bone union was observed.

The clinical examination included assessments of balance (Figure 3) and weight distribution over the lower limbs (Figure 4).

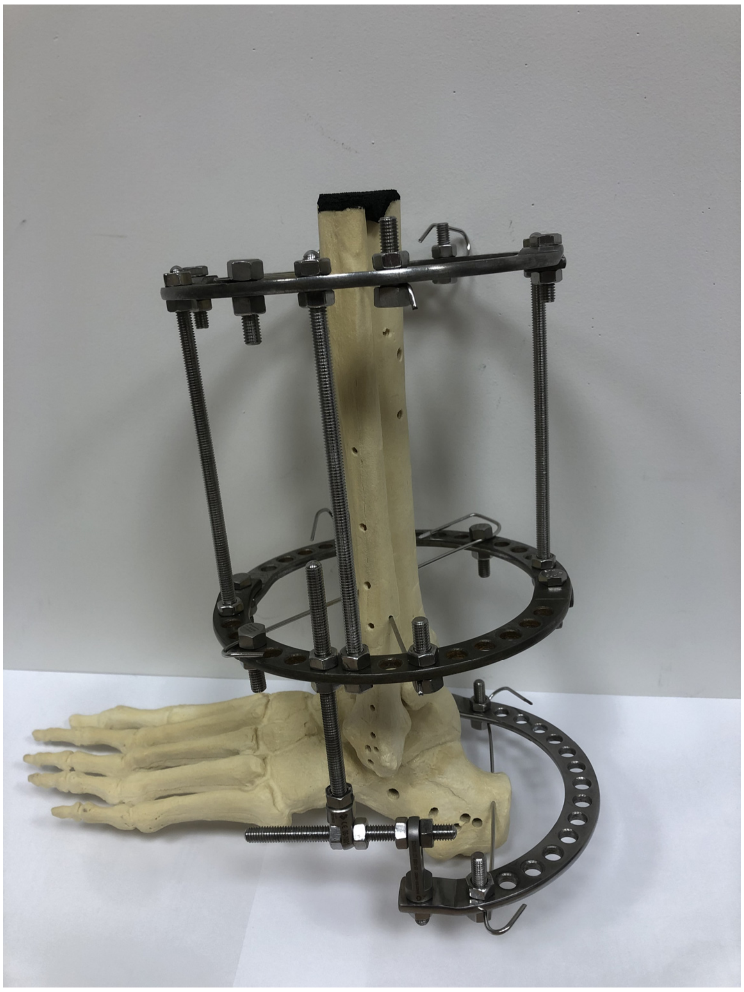

Figure 1. A three-dimensional model of the Polish modification of an Ilizarov fixator for calcaneal fracture treatment.

The device used was a FreeMED MAXI pedobarographic platform manufactured by SensorMedica (Guidonia Montecelio, Rome, Italy). The pedobarographic assessment set includes a platform measuring 63.5 × 70 cm (total active sensor area of 50 × 60 cm), two inactive mats measuring 70 × 100 cm each, and a computer with appropriate software, Figure 5.

The platform can measure pressures of up to 150 N/cm^2 with a minimum acquisition frequency of 300 Hz in real time. The 3000 square resistive sensors coated in 24-carat gold, each with a durability of 1,000,000 cycles, ensure high accuracy and reproducibility of measurements [26–29,35,36].

Each study subject had received detailed instructions on the measurement procedure. During pedobarographic and posturographic assessments, each subject was asked to make corrective adjustments to his or her posture. The measurements were taken while the subjects had their eyes open and were standing on both lower limbs, with their feet positioned freely in a physiological position (with an external rotation of 5–10°) [30]. The mean duration of balance assessments was 51.2 s. Weight distribution was recorded following a 5-second stabilization after a subject stepped onto the platform. The subjects were advised to maintain an upright posture, with their arms hanging symmetrically along the torso, and to keep their eyes fixed on one point on the wall in front of them at their eye level. Each subject underwent the measurement three times, and the mean value of the three was used in further analyses. The measurements were recorded via

FreeSTEP software, V.2.02.006. Subsequently, the results were exported onto a spreadsheet and analyzed statistically.

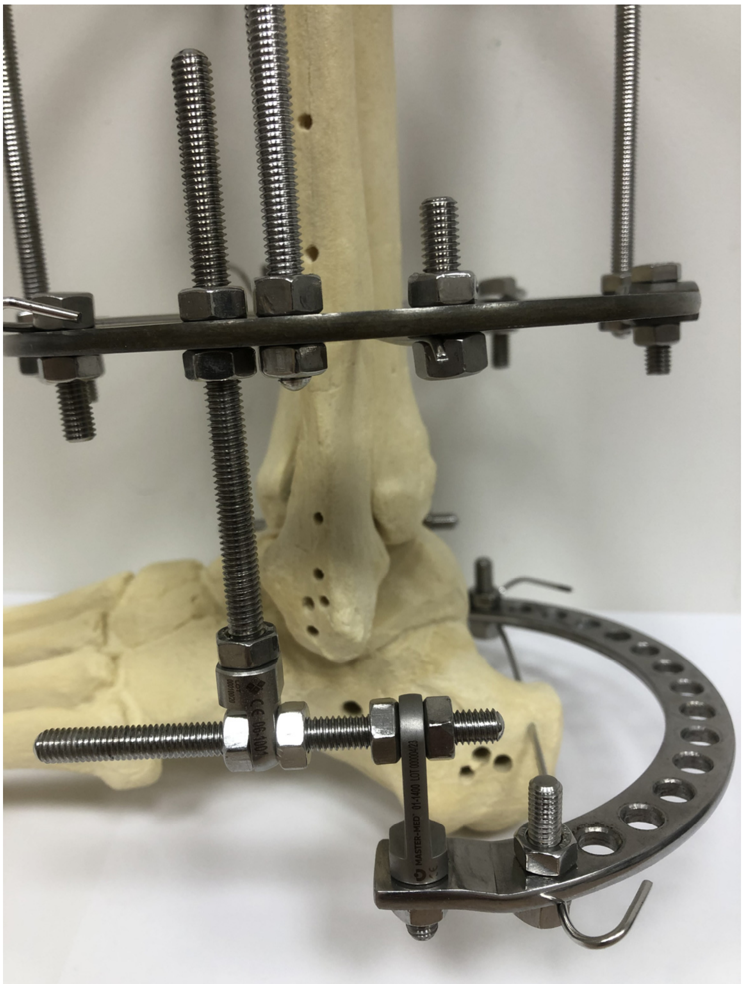

Figure 2. Detailed structure of an Ilizarov fixator.

Balance was assessed based on center-of-gravity displacement. This parameter was expressed as the total distance (in millimeters) traversed by the center of gravity over the course of the evaluation [15–17,27]. Balance assessment was also based on the surface area determined by maximum displacements of the center of gravity and defined as the area (in mm^2) enclosed by the points of maximum center-of-gravity displacement in all directions over the course of the evaluation [15–17,27].

Weight distribution over the lower limbs was expressed in percentage values. In the experimental group, we assessed the load on the uninjured and the treated lower limb and calculated the proportion of weight distribution on the forefoot and hindfoot of either limb. The dominant limbs in the control group of healthy individuals were compared with the uninjured limbs of treated individuals, and the non-dominant limbs of control individuals were compared with the operated limbs of treated individuals [15,16,18]. The results obtained in the experimental group of patients with calcaneal fractures treated with the Ilizarov method were compared with those obtained in the control group of healthy volunteers.

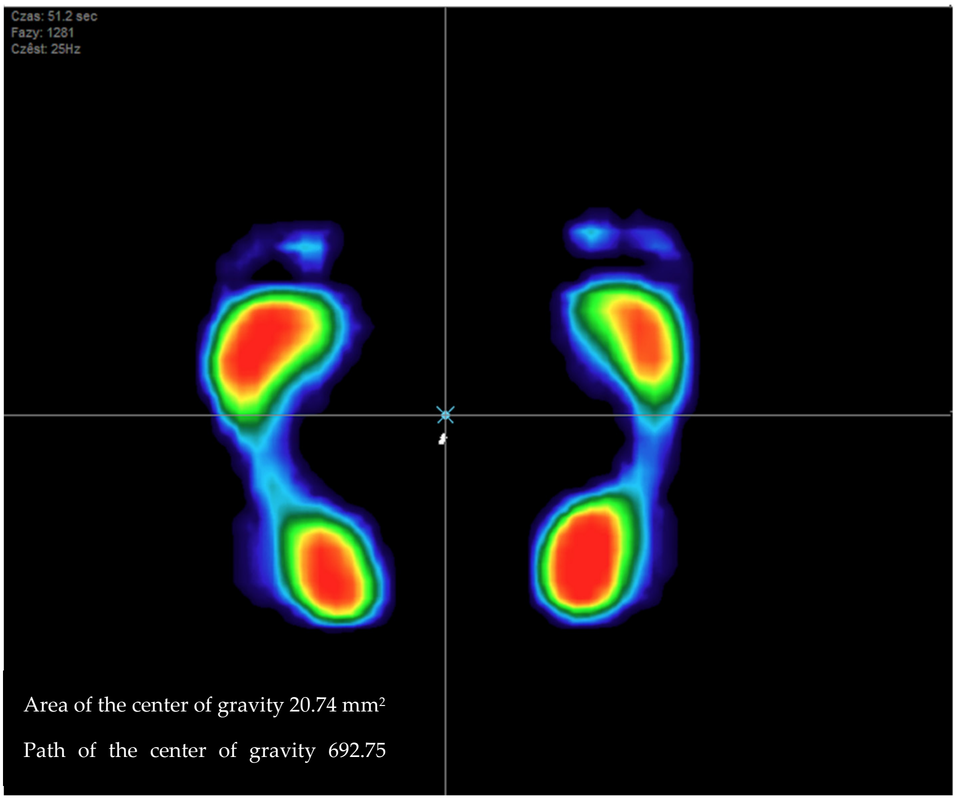

Figure 3. Image of balance test.

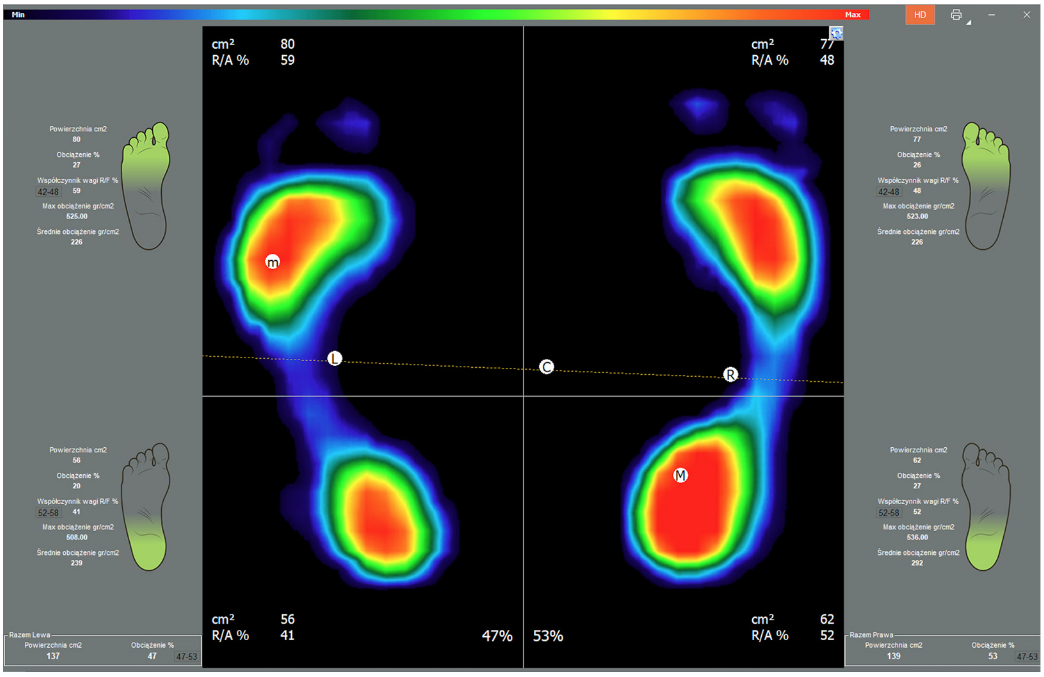

Figure 4. Image of the percentage weight distribution over the limbs. Color map of the pressures: red to dark green—from the area of the highest to the lowest level of pressure; blue—foot perimeter.

Figure 5. SensorMedica pedobarographic platform.

Statistical Analysis

Data were statistically analyzed using Statistica 13.1. The Shapiro–Wilk test was used to check for normality of distribution. Continuous variables were reported as mean (±SD). A Levene's test was performed to assess the homogeneity of variance within the two repeat sets of measurements. Inter-group comparisons of continuous variables were made with Student's *t*-test. The level of statistical significance was set at $p < 0.05$.

3. Results

The mean displacement of the center of gravity in the experimental group was significantly higher at 1307.31 mm than in the control group (896.34 mm; $p = 0.038$), (Figure 6, Table 1). The mean area of the center of gravity was 162.77 mm^2 in the experimental group and 96.67 mm^2 in the control group. This difference between groups was not statistically significant (Table 1).

Table 1. Path of center of gravity and area of the center of gravity.

Analyzed Variable	Patients	Control Group	*p*-Value *
	Mean ± Standard Deviation		
Area of the center of gravity [mm^2]	162.77 ± 132.85	96.67 ± 73.89	0.324
Path of the center of gravity [mm]	1307.31 ± 372.33	896.34 ± 272.89	0.038

* Student's *t*-test.

An analysis of weight distribution over the operated and uninjured limb in the experimental group and the non-dominant and dominant limb, respectively, in the control group revealed no significant differences (Table 2).

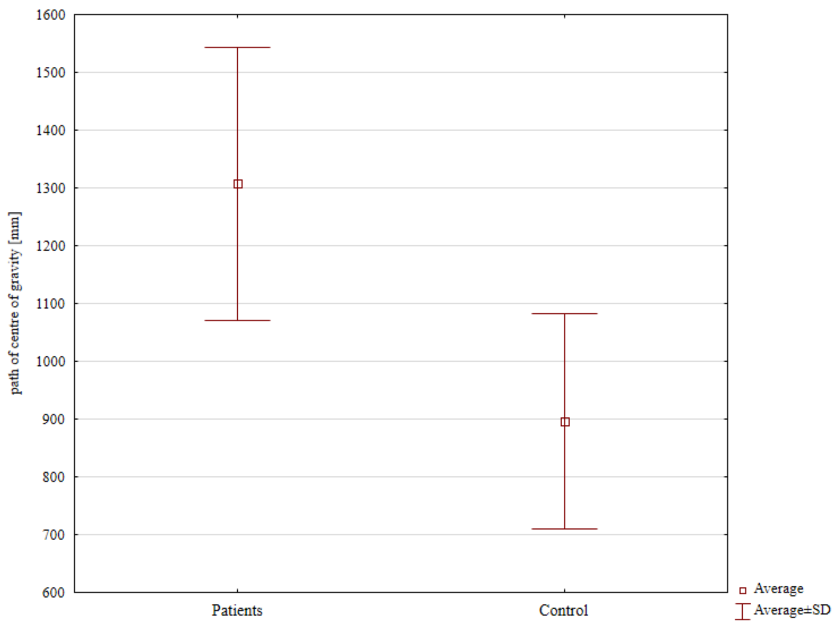

Figure 6. Path of the center of gravity in the experimental group compared with that in the control group.

Table 2. Body weight distribution in patients after treatment and in controls.

Loads on Limb	Control Group	Patients after Surgery
	Mean ± Standard Deviation	
OL [%]	47.16 ± 2.97	46.01 ± 5.67
NOL [%]	52.83 ± 13.72	53.11 ± 7.23
p-value *	0.715	0.077
OL forefoot [%]	23.66 ± 3.7	19.22 ± 4.79
NOL forefoot [%]	26.41 ± 4.75	25.33 ± 6.57
p-value *	0.128	0.038
OL hindfoot [%]	23.5 ± 3.06	27.66 ± 6.34
NOL hindfoot [%]	26.41 ± 4.81	27.77 ± 4.54
p-value *	0.090	0.966

OL—operated limb; NOL—non-operated limb. * Student's *t*-test.

Nonetheless, it is worth noting that patients treated with the Polish modification of the Ilizarov method tended to bear significantly less weight on the forefoot of the operated limb (19.22%) in comparison with that of the uninjured limb (25.33%), $p = 0.038$ (Table 2, Figure 7). We observed no significant differences in the proportion of weight borne on the hindfoot in the two study groups (Table 2).

The forefoot of the operated limbs in the experimental group also bore significantly less weight (19.22%) than that in the non-dominant limbs in the control group (23.66%), $p = 0.026$, (Table 3, Figure 8).

Table 3. Body weight distribution in the two groups.

Analyzed Variable	Patients	Control Group	*p*-Value *
	Mean ± Standard Deviation		
OL [%]	46.01 ± 5.67	47.16 ± 2.97	0.668
NOL [%]	53.11 ± 7.23	52.83 ± 13.72	0.390
OL forefoot [%]	19.22 ± 2.79	23.66 ± 2.71	0.026
OL hindfoot [%]	27.66 ± 5.34	23.5 ± 3.06	0.060
NOL forefoot [%]	25.33 ± 6.57	26.41 ± 4.75	0.666
NOL hindfoot [%]	27.77 ± 4.54	26.42 ± 4.81	0.519

OL—operated limb; NOL—non-operated limb. * Student's *t*-test.

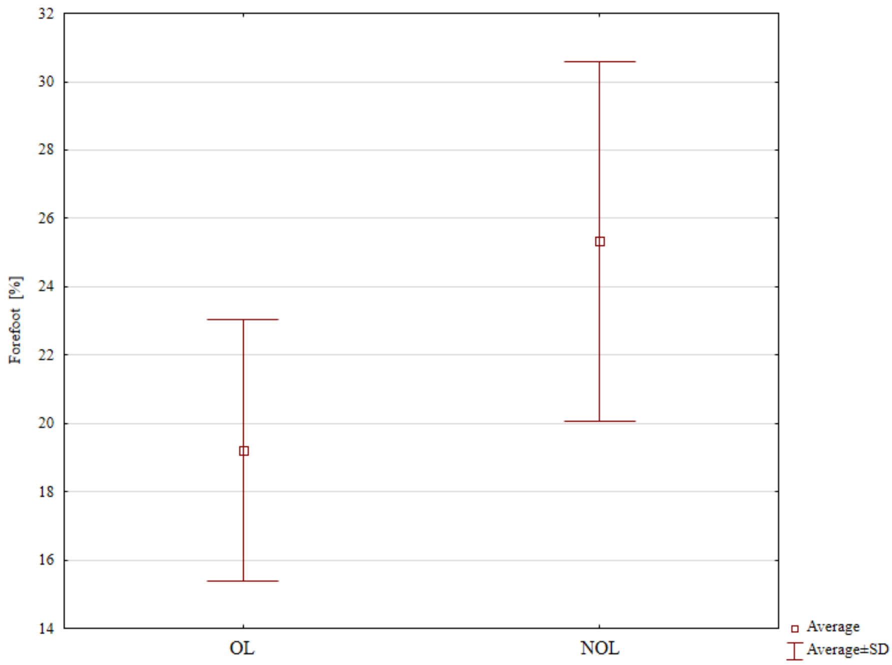

Figure 7. Weight distribution in the forefoot of the operated and the uninjured limbs.

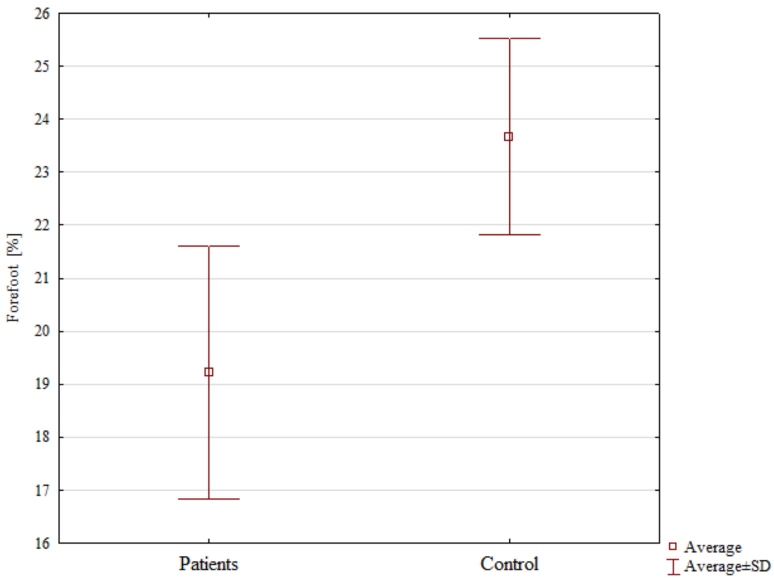

Figure 8. A comparison of weight distribution in the forefoot of the operated limb in the experimental group and that of the non-dominant limb in the control group.

We observed no significant differences in the percentage of weight distribution between the operated limb in the experimental group and the non-dominant limb in the control group, or between the uninjured limb in the experimental group and the dominant limb in the control group (Table 3). Moreover, these compared pairs of limbs showed no significant differences in terms of any other analyzed parameters (Tables 2 and 3).

4. Discussion

This paper presents our assessment of balance and weight distribution over the lower limbs following calcaneal fracture treatment with the Polish modification of the Ilizarov external fixator. We observed no differences in the percentage distribution of weight over the lower limbs between any of the following pairs of compared limbs: the operated and uninjured limbs in the experimental group; the operated limb in the experimental group and the non-dominant limb in the control group; and the uninjured limb in the experimental group and the dominant limb in the control group. The analysis of balance showed some of the results to be significantly poorer in the group of calcaneal fracture patients than in the group of healthy volunteers, which partly supports our hypothesis. The mean displacement of the center of gravity in the experimental group was not as good as that in the control group, whereas the mean area of the center of gravity was comparable in both groups.

Intra-articular calcaneal fractures often pose a challenge for orthopedic surgeons due to the complexity of the required surgery and high rates of complications [1–4,6,7,9–13,22,33,34]. The Ilizarov method has been adopted as one of the techniques used in the treatment of calcaneal fractures [2–14].

The goal of surgical treatment of intra-articular calcaneal fractures is to reduce pain and restore the three-dimensional structure of the calcaneus and the function of the foot [1,2,4–7,22].

Calcaneal fractures may lead to a lowered longitudinal arch, which results in flatfoot [23]. Some authors suggest that the normal shape and restored anatomical structure of the calcaneus determines normal lower-limb biomechanics and gait efficiency [1,2,4,6]. However, other authors reported good clinical and functional outcomes with poor radiological outcomes [1], and others reported poor clinical or functional outcomes with good radiological outcomes [2,7]. Achieving normal musculoskeletal biomechanics—including balance and weight distribution over the lower limbs—following treatment of musculoskeletal pathologies is possible in the case of normal ranges of motion, absence of pain, and restored bone anatomy [15–24]. Typically, weight distribution over the lower limbs is symmetrical [16,17]. In light of the above, it is important not only to conduct clinical and radiological assessments but also to assess balance and weight distribution over the lower limbs, as it is performed in analyzing treatment outcomes in various musculoskeletal pathologies, including injury-induced ones [15–25,31–34,36]. Abnormal biomechanical parameters, including balance and distribution of weight over the lower limbs, may indicate postoperative pain, limited range of motion, and decreased muscle strength, hence the great importance of lower-limb biomechanics assessments following treatment [15–25,31–34,36].

There have been no studies to assess lower-limb biomechanics following the treatment of calcaneal fractures with the Ilizarov method. Authors of earlier studies on gait reported abnormal gait parameters following calcaneal fractures treated with open reduction and internal plate fixation [22–25]. Some authors reported no differences between the treated and the uninjured limbs in terms of the mean contact area in the forefoot and hindfoot in patients after calcaneal fracture treatment with an open reduction and internal plate fixation approach but they assessed neither balance parameters nor percentage weight distribution over the lower limbs [34]. The group of patients who received conservative treatment for calcaneal fractures exhibited abnormal biomechanics between the treated and the uninjured limb in terms of the mean contact area in the forefoot and hindfoot [34]. Other authors reported differences between the treated and the uninjured limbs in terms of maximum pressure and total contact time in patients with calcaneal fractures treated with internal plate fixation [33]. There have been no reports of assessing balance and weight distribution over the lower limbs following calcaneal fracture treatment.

Theoretically, the Ilizarov method is more effective in restoring balance and weight distribution than other available treatments for calcaneal fractures (such as open reduction and fixation with a plate or screws). In comparison with other techniques of calcaneal fracture fixation, the Ilizarov method is less invasive, requires only a small incision, and is associated with a lower risk of infections and other complications [1–4,6,7,9–13]. In comparison with calcaneal fracture fixation with a plate or screws, the Ilizarov method allows patients to bear weight on the operated limb sooner and initiate intensive rehabilitation sooner than with other treatment methods.

Pajchert-Kozłowska et al. used a pedobarographic platform to assess balance in patients following treatment of tibial nonunion with the Ilizarov method [15]. Those authors reported the balance parameters in the experimental group to be comparable with those in healthy volunteers [15]. Another study, which evaluated patients following lower-limb corticotomy procedures with the Ilizarov method, showed poorer balance values in comparison with those in the healthy control group [16]. Analysis of balance following ankle joint arthrodesis with internal fixation or with external fixation with the Ilizarov method showed worse results in the group with internal fixation [17]. Rongies used a pedobarographic platform to assess 21 patients with coxarthrosis and reported balance improvement following rehabilitation [19].

In our group of patients, center-of-gravity displacement was significantly greater than that in the control group of healthy individuals. The area of the center of gravity in the experimental group was greater, though not significantly, than that in the control group. This suggests a lack of balance normalization following calcaneal fracture treatment with the Ilizarov method. Calcaneal fractures may result in swelling, reduced muscle strength, pain, and a limited range of motion [22,24], which may have adversely affected the balance in our experimental group. The balance parameters in our patients were comparable with those reported by authors who assessed patients after corticotomies using the Ilizarov method and after ankle joint arthrodeses using the Ilizarov method [16,17]. The fact that some balance parameters remained abnormal after calcaneal fracture treatment with the Ilizarov method indicates the need for a longer rehabilitation period and exercises for these patients.

In another group of 57 patients treated with lower-limb croticotomy with the Ilizarov method, there were no differences in the percentage weight distribution over the lower limbs between the operated and non-operated limb, and the absolute load values were comparable with those obtained in the healthy control group [16]. Analysis of percentage weight distribution over the lower limbs in patients treated with ankle joint arthrodesis with internal fixation and in those treated with an external Ilizarov fixator revealed no differences between the two groups in terms of weight distribution between the operated and the uninjured limb [17]. Pawik et al. assessed patients with tibial nonunion treated with the Ilizarov method [18]. Those authors observed no differences in the percentage weight distribution between the forefoot and hindfoot of either the operated and uninjured limb in the experimental group or between the experimental and control groups [18]. Güven et al. analyzed 37 patients who underwent surgical treatment of transtrochanteric femoral fractures with partial hemiarthroplasty or proximal femoral nail [31]. Using a pedobarographic platform, those authors assessed the differences in weight distribution between the operated and uninjured limbs in static conditions. The results showed a greater load on the uninjured limb in both analyzed groups [31]. Out of the 26 patients with isolated tarsometatarsal (Lisfranc) joint injuries evaluated by Shepers et al., one-half received surgical treatment and the other half received conservative treatment [32]. Study results showed both groups to have similar percentage weight distribution over the lower limbs. In the case of the injured foot, there was a significantly greater weight distribution on the posterior part of the foot than on the forefoot [32]. Tarczyńska et al. conducted a balance study on 30 patients, assessing the long-term effects of surgical treatment of Achilles tendon injury [36]. They compared two groups of patients: one who sought treatment within 4 weeks of the injury and the other who sought treatment after 4 weeks. Their results showed that delayed treatment of Achilles tendon injury leads to deterioration of balance parameters in long-term follow-up [36].

A fracture reduction that recreates the anatomical structure of the calcaneus helps restore the normal biomechanic parameters and three-dimensional structure of the foot and gain efficiency [1,2,4,6]. Our study showed a symmetrical percentage weight distribution between the operated and the uninjured limb in the experimental group. Similarly, we observed no differences in weight distribution between the operated limb in the experimental group and the non-dominant limb in the control group or between the uninjured limb in the experimental group and the dominant limb in the control group. The only statistically significant difference was in terms of forefoot loading, which was significantly lesser in the operated than in the uninjured limb in the experimental group. This indicates a normalization of percentage weight distribution over the lower limbs following fracture treatment with the Ilizarov method. The patients who underwent calcaneal fracture treatment with the Polish modification of the Ilizarov method achieved comparable percentage values of weight distribution over the lower limbs to those in the control group of healthy volunteers. The results of weight distribution over the lower limbs observed in our study are comparable with those reported in the literature [16–18].

One limitation of our study is its retrospective nature. This is due to the nature of injuries since patients with calcaneal fractures cannot undergo a normal pedobarographic assessment prior to treatment. Other authors also presented retrospective analyses of patients following calcaneal fracture treatment and retrospective pedobarographic analyses [3–6,8–10,12–18,22–25,31,33,34]. Another limitation of our study is the relatively small sample size. This is due to the low incidence of calcaneal fractures and the time constraints for pedobarographic assessments. However, many other authors assessed comparable or even smaller study groups [3–6,8–10,12–15,18–20,23,25,32–34,36]. One of the strengths of our study is the sex-, age-, and BMI-matched control group, a uniform rehabilitation protocol, the follow-up period of over 2 years, and all procedures being conducted by the same surgeon. In the future, we are planning to conduct similar studies in a larger patient population with a longer follow-up period and to assess gait parameters in patients with intra-articular calcaneal fractures treated with the Ilizarov method. We believe it is important to compare the balance parameters and percentage weight distribution over the lower limbs in patients following calcaneal fracture treatment with different fixation techniques (i.e., an external Ilizarov fixator vs. open reduction and internal fixation with a plate and screws). Our study showed that normal balance parameters were not restored following treatment; however, they were similar to those achieved by other patients following treatment with an Ilizarov fixator [16,17]. The fact that some balance parameters did not reach their normal values in our patients may be due to pain, a limited range of motion, swelling, and reduced muscle strength [15–25,31,32]. We are planning to conduct studies to assess the severity of pain, joint range of motion, muscle strength, and quality of life in patients following calcaneal fracture treatment with the Ilizarov method.

Our study showed that some balance parameters did not reach their normal values following calcaneal fracture treatment with the Ilizarov method. We believe that more attention should be paid to patient rehabilitation following calcaneal fracture treatment with the Ilizarov method. These patients should undergo a longer and more intense rehabilitation and have a longer period of follow-up visits. A longer period of post-treatment analgesia and exercises should be considered for patients following calcaneal fracture treatment with the Ilizarov method. Implementing these measures may help reduce pain and swelling and improve range of motion and muscle strength, which would restore normal biomechanical parameters in patients following calcaneal fracture treatment with the Ilizarov method.

5. Conclusions

The use of the Ilizarov method in calcaneal fracture treatment helps achieve normalization of percentage weight distribution in the lower limbs, with the results comparable with those obtained in the healthy control group.

Following treatment, calcaneal fracture patients showed worse mean displacement of the center of gravity than that in the control group, with no differences between these two groups in the mean area of the center of gravity.

Treatment of calcaneal fractures with the Ilizarov method does not help achieve completely normal static parameters of lower-limb biomechanics.

Patients with calcaneal fractures treated with the Ilizarov method require longer and more intense rehabilitation and follow-up periods.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in this study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

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Assessment of Function in Patients after Calcaneal Fracture Treatment with the Ilizarov Method

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Abstract: Background: Up to 75% of calcaneal fractures are intra-articular fractures, which may severely impair foot function and lead to disability. **Methods:** We retrospectively analyzed 21 patients with intra-articular calcaneal fractures who had been treated with the Ilizarov method in the period 2021–2022. The mean patient age was 47 years (range 25–67 years). We analyzed the following functional parameters: foot function with a revised foot function index (FFI-R) questionnaire and the level of physical activity, with the University of California Los Angeles (UCLA) activity scale, a visual analog scale (VAS), and a Grimby physical activity level scale; and ankle range of motion. **Results:** We observed a significant improvement in the UCLA activity scores and Grimby activity score at long-term follow-up. Functional outcomes based on the FFI-R questionnaires showed an improvement, from 292 points prior to surgery to 127 points at follow-up, $p = 0.013$. The post-treatment follow-up measurements revealed a median dorsiflexion at the treated ankle joint of 20 degrees, whereas that at the intact ankle was 40 degrees, $p = 0.007$. The plantar flexion showed asymmetry, with a median 15 degrees at the treated ankle and 30 degrees at the intact ankle, $p = 0.007$. The median range of inversion at the ankle joint was 5 degrees in the treated limb and 15 degrees in the intact limb, $p = 0.039$. **Conclusions:** Patients with calcaneal fractures treated with the Ilizarov method are recommended to have a longer and more intensive rehabilitation. The range of ankle motion in the treated limb was limited in comparison with that in the intact limb; however, this did not greatly affect the patients' return to their earlier, pre-injury level of physical activity.

Keywords: calcaneal fracture; Ilizarov method; functional assessment; physical activity; range of motion

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1. Introduction

Calcaneal fractures are among the most common tarsal fractures and usually result from high-energy trauma, such as road traffic accidents or falls from heights [1–4]. Up to 75% of calcaneal fractures are intra-articular fractures, which may severely impair foot function and lead to disability [2,4–7]. Regaining full functionality often requires a long time, and a number of patients struggle with reaching pre-injury levels of activity [2–4,7,8]. Consequently, calcaneal fractures have a considerable socioeconomic impact, since they mostly affect the working-age population [4,7,9]. Walking begins with placing the foot on the heel, which is why effective treatment of calcaneal fractures is so important and crucial [5,8]. Unfortunately, despite the development of techniques for internal and external stabilization of calcaneal fractures, there are no ideal methods of treating calcaneal fractures. Treatment of calcaneal fractures is often still difficult for surgeons and does not always provide good treatment results [2–7,10–24]. Treatment methods for intra-articular calcaneal fractures are a subject of ongoing discussions [3,10–13]. Some experts recommend open reduction and internal fixation [4,6,7,14], while others prefer the use of external fixators [2,3,5,8,10–12].

Despite advances in surgical techniques involving open reduction and internal fixation via lateral access, the functional outcomes are unsatisfactory in many cases [7,11,13].

The results from some studies on surgical techniques suggest that minimally invasive approaches and percutaneous reduction and stabilization methods are superior to traditional open reduction methods. In particular, the use of minimally invasive techniques is associated with a lower risk of complications related to soft tissue damage, resulting in shorter recovery times and better overall treatment outcomes [24]. Open reduction and internal fixation of calcaneal fractures are associated with a high risk of complications, reaching up to 33% [6,11–13]. The most common complications in open reduction and internal stabilization of calcaneal fractures include infections, delayed wound healing, soft tissue necrosis, and destabilization of the implants [6,11–13]. Another technique used in calcaneal fracture treatment is the Ilizarov method [5,6,8,10–13,15,16]. This involves external fixation of bone fragments and the restoration of calcaneal bone shape and foot structure [5,8,11–13]. Achieving the correct shape and three-dimensional structure of the calcaneus is one factor that determines good clinical outcomes and normal foot function in patients following surgical treatment [4–6,11–13]. Treatment of calcaneal fractures using external fixators, including the Ilizarov method, has an advantage over internal fixation with plates in the form of a lower incidence of complications, which is related to a less extensive surgical access [5,6,8,10–13,15,16]. The functional limitations observed after calcaneal fractures have been attributed to limited mobility, stiffness, and pain at the ankle joint [4,5,11]. However, they might be due to an altered geometric morphometry of the calcaneus and an uneven articular surface (posterior facet) [4,5,7,17]. Therefore, it is important to monitor ankle joint mobility and function parameters after calcaneal fracture treatment, starting from early stages of rehabilitation. This approach allows for therapeutic process adjustments, helps patients regain full functionality more rapidly, and reduces the risk of complications [17]. Previous Ilizarov treatment techniques for calcaneal fractures described the use of at least three Kirschner wires to stabilize the foot [10–13,15]. The greater the number of implants placed in the foot, the greater the risk of complications, including infection, swelling, and delayed wound healing [5,8,11]. The Polish modification of the Ilizarov method in the treatment of calcaneal fractures allows the foot to be stabilized with only one Kirschner wire [5,8]. Theoretically, a smaller number of implants placed in the foot during the treatment of calcaneal fractures should be associated with fewer complications and allow for better functional results of treatment [5,8].

Pelc et al., who assessed balance and weight distribution in the lower limbs following calcaneal fracture treatment with the Ilizarov method, reported normalized weight distribution and no differences between the patient group and the control group in the mean center of gravity sway area [8]. It was only the mean displacement of the center of gravity that was greater in the patient group than in the controls [8]. The available literature contains no studies assessing ankle functionality, activity levels, and the range of motion following calcaneal fracture treatment with the Ilizarov method. There have been only a handful of studies evaluating the range of motion at the ankle after calcaneal fracture treatment [18–20]; however, those patients had not been treated with the Ilizarov method. One study assessed the ankle functional capacity in patients after calcaneal fracture treatment with internal fixation [14].

We posed the hypothesis that the use of the Ilizarov method in treating calcaneal fractures will help improve functional parameters and the range of motion at the ankle joint and the levels of physical activity.

The purpose of our study was to assess functional outcomes after calcaneal fracture treatment with a Polish modification of the Ilizarov method.

2. Materials and Methods

This study was retrospective in nature. We analyzed patients with intra-articular calcaneal fractures who had been treated (at one center) with the use of a Polish modification of the Ilizarov method (Figure 1) in the period 2021–2022. Study inclusion criteria were a minimum follow-up of 2 years after treatment completion, intra-articular calcaneal fracture treated with a Polish modification of the Ilizarov method by the same orthopedic surgeon, complete medical records and data from functional assessment questionnaires (physical activity questionnaire, range of motion at the ankle joint), a lack of lower limb comorbidities, and informed consent to voluntarily participate in this study, with the option of withdrawing from the study at any time.

Figure 1. Model of the Polish modification of the Ilizarov external fixator in the treatment of calcaneal fractures.

Those individuals who did not meet the above criteria were excluded from the study. This study was approved by the local ethics committee (Approval No. UO/0023/KB/2023). The study was conducted in accordance with the Declaration of Helsinki. All patients participating in the study gave voluntary and informed consent. All patients were informed about the voluntary nature of the study and about the possibility of resigning from participation in the study at any stage.

All patients underwent diagnostic imaging in the form of X-rays of the foot in AP and lateral projections, an axial image of the calcaneus and computed tomography of the foot and ankle joint. Patients in the emergency department were treated immediately after injury in a short leg cast. Stabilization of a calcaneal fracture using the Ilizarov method was performed by an experienced orthopedist. The operation was performed within 3 to 5 days of the fracture, depending on the availability of the operating room and the presence of the operator at work. Surgical treatment of calcaneal fractures was conducted with the use of a Polish modification of the Ilizarov external fixation method [5,8], shown in Figure 1. The external fixator was composed of two rings (secured to crural bones with Kirschner wires) and one half ring secured to the calcaneus with a Kirschner wire. The first Kirschner wire was inserted under fluoroscopy into the most proximal and dorsal calcaneal bone fragment. Subsequently, the half ring fixated to the calcaneus was secured to the distal leg ring via two connectors (composed of two perpendicular, threaded rods). Once the fixator was mounted onto the foot and leg, the calcaneal fracture was reduced under fluoroscopy. The Polish modification of the Ilizarov external fixator enables stabilization and a reduction in calcaneal fracture using only one Kirschner wire inserted into the calcaneus [5,8]. Thanks to the Polish modification of the Ilizarov external fixator, it is possible to stretch and correct the position of bone fragments in the frontal and sagittal planes [5,8]. The Polish modification of the Ilizarov external fixator design also enables the correction of valgus or varus deformation of the calcaneus [5,8]. The Ilizarov external fixator design we use also enables arthrodiastasis of the ankle joint and talocalcaneal joint, which is beneficial in the treatment process [5,11,13]. Postoperative rehabilitation was conducted according to a single protocol. On day one after surgery, the patients began walking with the use of two elbow crutches while bearing partial weight on the treated limb. Weight bearing was gradually increased, to the extent allowed by the patient's pain tolerance. Pre-scheduled follow-up visits were to assess the progress of treatment. If the wounds healed well, patients were discharged home from the hospital ward on the first day after surgery. Follow-up X-rays were taken on the day of the procedure, two and six weeks after the procedure, and then every four weeks until bone union was achieved. When clinical and radiological evidence of union was observed, the fixator was loosened and the patient was allowed to walk with full weight bearing. The fixator was removed 7 days after it was loosened when a follow-up X-ray film showed no bone fragment displacement.

Study inclusion criteria restricted the study group to 21 patients, including 7 women and 14 men, who were treated for intra-articular calcaneal fracture. The Sanders classification-based fracture types in our patients were type 2 in three cases, type 3 in five cases, and type 4 in 13 cases. The mean patient age was 47 years (range 25–67 years), the mean body weight was 81 kg (range 61–130 kg), the mean height was 171 cm (range 152–188 cm), and the mean body mass index was 28 (range 24–40).

In our study, we analyzed the following functional parameters: foot function with a revised foot function index (FFI-R) questionnaire [25,26] (Figure 2) and the level of physical activity, with a 10-point University of California Los Angeles (UCLA) activity scale [27], a 10-point activity visual analog scale (VAS) [28] (Figure 3), and a 6-point Grimby physical activity level scale [29].

In the study, we used an extended form of the foot function index-revised (FFI-R) questionnaire [25,26], which was created to measure foot function. It contains five subscales and a total of 68 questions. These subscales include foot pain (11 items), stiffness (8 items), difficulty related to foot functioning (20 items), activity limitation (10 items), and social functioning (19 items). All items in the questionnaire were based on a 6-point response scale, which was modified accordingly for each; for example, for the pain subscale: 1 = no pain, 2 = mild pain, 3 = moderate pain, 4 = severe pain, 5 = very severe pain, 6 = worst pain imaginable. On this scale, zero means the best functional result of the foot, while the higher the score, the worse the foot function. Additionally, we used the UCLA activity scale to assess the level of physical activity [27]. The level of physical activity was assessed on a 10-point scale based on 10 descriptive levels of activity. Each level of this scale corresponded to specific types of physical activity, ranging from very low activity (e.g., a sedentary lifestyle) to very high activity (e.g., regular participation in sports requiring high physical exertion). In the questionnaire, participants were asked about their participation in various activities and physical activities, and the researcher assessed and assigned them to the appropriate level. The activity visual analog scale (VAS) for assessing physical activity allowed for a subjective assessment of one's physical activity over a specific period of time [28]. This scale included two extreme points: a point of 0 was a complete lack of physical activity, which indicated the lack of any form of movement or exercise. In turn, point 10 represented the highest possible level of physical activity, which referred to intense, regular, and demanding physical exercise. Subjects were asked to place their activity level on this scale, marking the point that they felt best reflected their daily physical activity. For the Grimby scale [29], designed to self-assess physical activity levels, activity levels were classified based on responses to the question: "Choose the one answer that best describes your level of physical activity". Patients were given six options that detailed different levels of physical activity: 1. Almost no physical activity, 2. Mostly sedentary lifestyle with occasional walking and gardening, 3. Light exercise, 4. Moderate exercise of less than 2 h per week, 5. Moderate exercise of at least 3 h a week, 6. Regular vigorous exercise. Before completing each questionnaire, all respondents were instructed in detail on how to complete them. The instructions were clear and precise to ensure that all questions were understood and the forms were completed correctly. While completing the questionnaires, respondents could ask for help or clarification at any time if they encountered any difficulties or ambiguities related to the content of the questionnaire. This ensured that the collected data were of a high quality and reliable.

Foot Function Index (FFI)

Scale	Questions	Scoring
Pain	• Before you get up in the morning • First pain standing without shoes • First pain walking without shoes • First pain standing with shoes • First pain walking with shoes • Pain standing with custom shoe inserts • Pain walking with custom shoe inserts • How is your pain at the end of the day • Pain with foot cramps • Pain before sleep • How severe is your pain at its worst	Rated 0-6 per item, ranging from 1. No pain 2. Mild pain 3. Moderate pain 4. Severe pain 5. Very severe pain 6. Worst pain imaginable
Stiffness	• Stiffness before getting up in the morning • Stiffness standing without shoes • Stiffness walking without shoes • Stiffness standing with shoes • Stiffness walking with shoes • Stiffness walking with custom shoe inserts • Stiffness before sleep • Stiffness at worse	Rated 0-6 per item, ranging from 1. No stiffness 2. Mild stiffness 3. Moderate stiffness 4. Severe stiffness 5. Very severe stiffness 6. Worst stiffness imaginable
Disability	• Walking around the house • Walking outside on uneven ground • Walking four or more blocks • Climbing stairs • Descending stairs • Getting out of chair • Standing normally • Standing tip toe • Carrying or lifting more than 5 pounds • Running • Fast walking • Walking downhill • Keeping regular walking pace • Walking regular distance • Keeping balance • Keeping foot clean • Walking with assistive devices • Because of hazards at home • Operating vehicle requiring foot to maneuver • Performing daily activities	Rated 0-6 per item, ranging from 1. No difficulty 2. Mild difficulty 3. Moderate difficulty 4. Severe difficulty 5. Very severe difficulty 6. So difficult unable
Limitation	• Use a cane, crutches, or a walker indoors • Use a cane, crutches, or a walker outdoors • Stay indoors all day due to feet • Stay in bed all day due to feet • Use an assistive device (stick, walker, crutches, frame) indoors • Use an assistive device outdoors • Take extra precautions when walking in crowds for fear of foot injury • Limit outdoor activity • Choose not to use public transportation • Choose not to drive	Rated 0-6 per item, ranging from 1. None of the time 2. A little of the time 3. Some of the time 4. Much of the time 5. Most of the time 6. All of the time
Quality of Life	• Fear of falling • Embarrassment due to limp • Difficulty finding fashionable footwear • Difficulty finding dress shoes • Embarrassment due to footwear • Depression from foot problems • Difficulty finding suitable footwear • Feeling awful because of foot problem • Limit social activities due to foot problems • Constant aggravation due to managing foot pain • Difficulty participating in social activities due to footwear • Aggravation in performing daily activities • Poor sleep because of foot pain • Burden of taking medication to control pain • Difficulty finding comfortable footwear • Difficulty finding employment • Concern with appearance of feet • Concern about limited work around house • Concern about possible amputation of foot, leg or toes	Rated 0-6 per item, ranging from 1. None of the time 2. A little of the time 3. Some of the time 4. Much of the time 5. Most of the time 6. All of the time

Figure 2. Foot function index-revised (FFI-R) questionnaire.

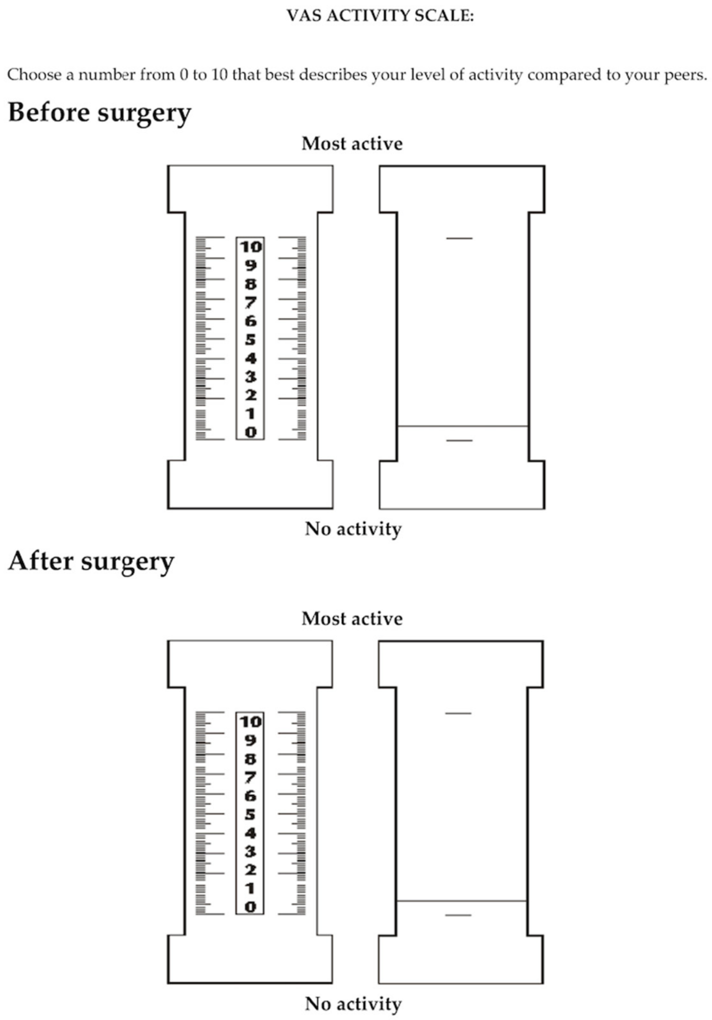

Figure 3. Ten-point activity visual analog scale (VAS).

We compared functional parameters before surgery and those obtained after long-term postoperative follow-up. Ankle range of motion was measured manually with a goniometer in the treated and healthy limb and included dorsiflexion, plantar flexion, inversion, and eversion, with the results expressed in degrees.

Statistical Analysis

Data were statistically analyzed using Statistica 13.3. The Shapiro–Wilk test was used to check for normality of distribution. The Wilcoxon signed-rank test was used to compare quantitative variables. The significance level was set at $p < 0.05$.

3. Results

We observed a significant improvement in the UCLA activity scores, with the median score increasing from 2 prior to surgery to 5 at follow-up, Z = 1.890, $p = 0.048$, shown in Table 1.

The Grimby activity score increased significantly from a median of 2 prior to surgery to 5 at long-term follow-up, Z = 2.267, $p = 0.023$, shown in Table 1 and Figure 4.

The level of physical activity assessed with VAS also showed improvement, from a median preoperative score of 3 to 6 at follow-up; however, this difference was not statistically significant, Z = 0.353, $p = 0.723$, shown in Table 1. Functional outcomes based on FFI-R questionnaires showed a considerable improvement, from a median score of

292 points prior to surgery to 127 points at follow-up, Z = 0.244, p = 0.013, shown in Figure 5 and Table 1.

Table 1. Detailed functional assessment of patients before and after surgery.

Analyzed Variable		Before Treatment	After Treatment	p *
		Value		
UCLA scale	Q1	1	4	0.048
	Median	2	5	
	Q3	7	6	
Gimbry scale	Q1	1	3	0.023
	Median	2	5	
	Q3	3	5	
VAS Activity Scale	Q1	0	5	0.723
	Median	3	6	
	Q3	8	8	
FFI-R scale	Q1	219	87	0.013
	Median	292	127	
	Q3	314	144	

* Wilcoxon signed-rank test; Q1, Q3—1st and 3rd quartile.

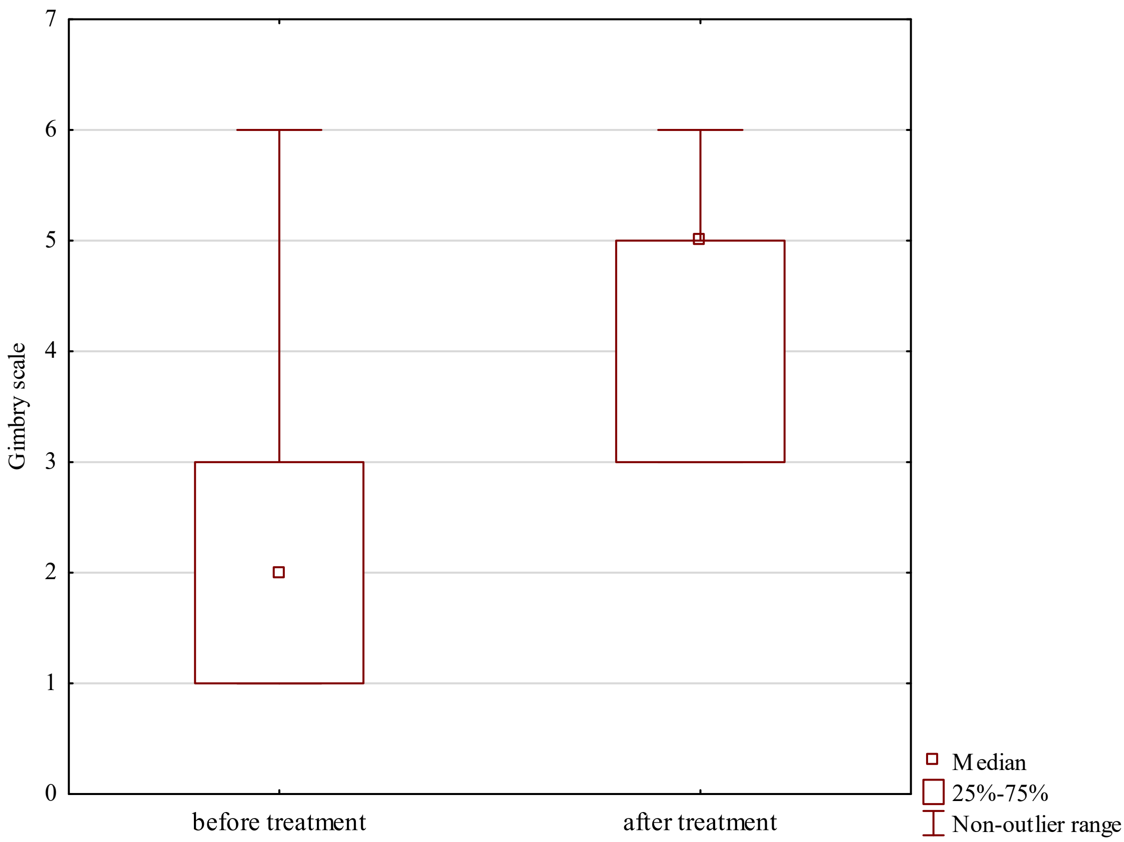

Figure 4. Grimby activity scores prior to and after treatment.

Post-treatment follow-up measurements revealed a median dorsiflexion at the treated ankle joint of 20 degrees, whereas that at the intact ankle was 40 degrees, Z = 2.666, p = 0.007, shown in Table 2 and Figure 6.

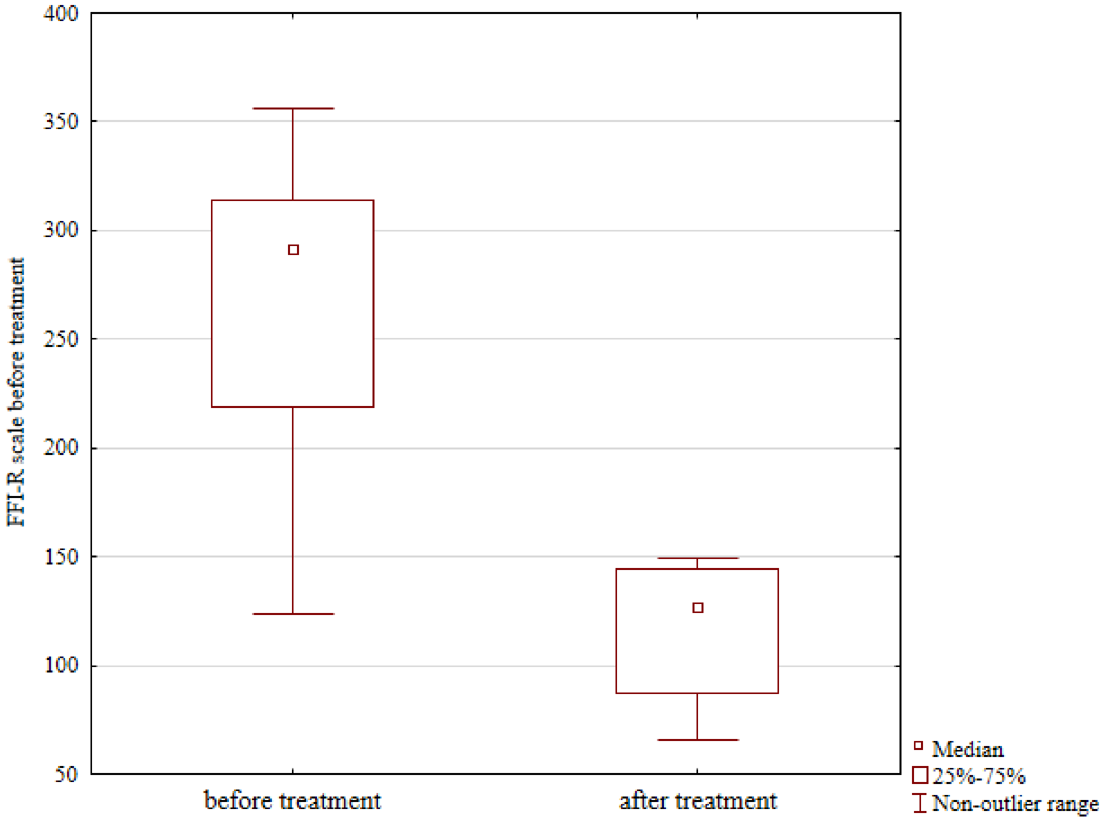

Figure 5. Functional outcomes prior to and after treatment, expressed as revised foot functional index (FFI-R) questionnaire scores.

Table 2. Detailed range of motion of patients.

Analyzed Variable		Operated Limbt	Non-Operated Limb	p *
	Value			
Dorsiflexion [degree]	Q1	8	35	0.007
	Median	20	40	
	Q3	25	50	
Plantar flexion [degree]	Q1	10	30	0.007
	Median	15	30	
	Q3	28	40	
Inversion [degree]	Q1	5	5	0.039
	Median	5	15	
	Q3	10	20	
Eversion [degree]	Q1	5	5	0.683
	Median	8	15	
	Q3	10	20	

* Wilcoxon signed-rank test; Q1, Q3—1st and 3rd quartile.

Plantar flexion showed a similar asymmetry, with a median 15 degrees at the treated ankle and 30 degrees at the intact ankle, Z = 1.874, $p = 0.007$, shown in Table 2 and Figure 7.

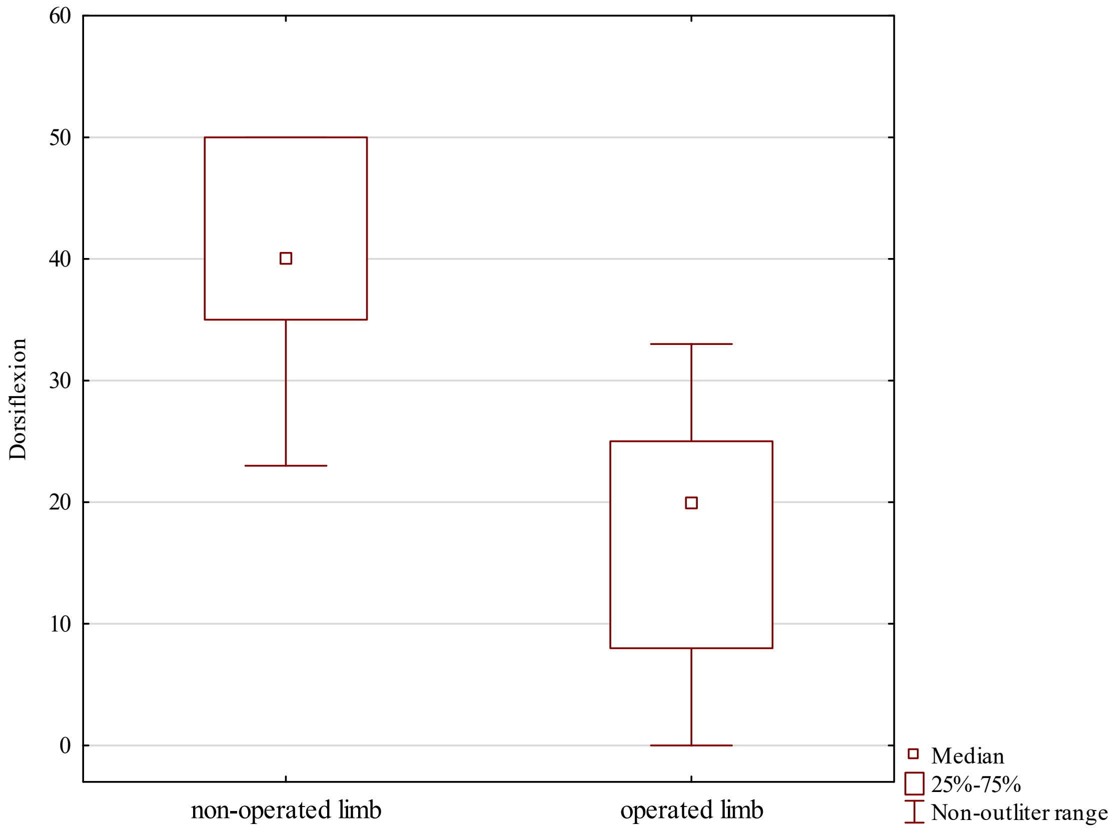

Figure 6. Foot dorsiflexion in the treated and intact limb.

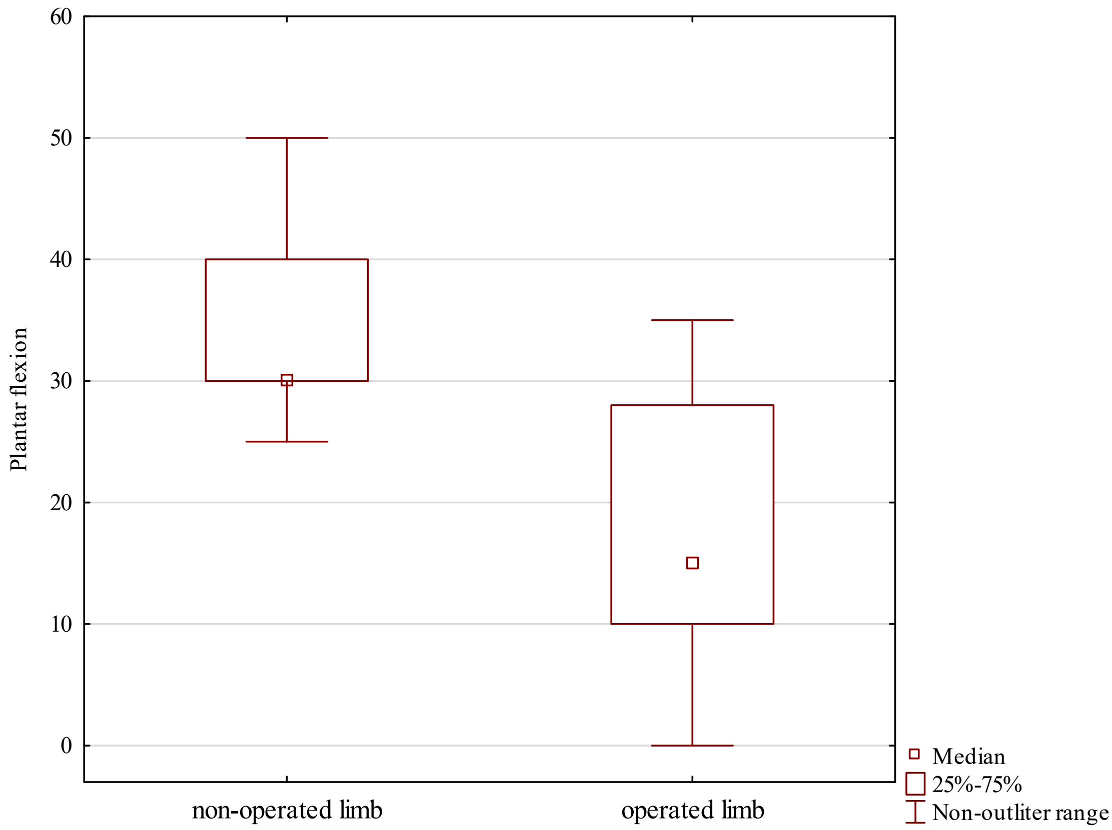

Figure 7. Foot plantar flexion in the treated and intact limb.

The median range of inversion at the ankle joint was 5 degrees in the treated limb and 15 degrees in the intact limb, with the difference being statistically significant, Z = 1.741, $p = 0.007$, shown in Table 2. The median range of eversion also showed a difference, with a median 8 degrees in the treated limb and 15 degrees in the intact limb; however, this difference was not statistically significant, Z = 0.325, $p = 0.683$, shown in Table 2.

4. Discussion

The aim of our study was to assess ankle functionality, the level of physical activity, and the range of motion at the ankle joint in patients with calcaneal fractures treated surgically with a Polish modification of the Ilizarov method. Following treatment, we observed a considerable improvement in the levels of activity measured via the UCLA and Grimby activity scores. There was also a significant post-treatment functional improvement measured with an FFI-R questionnaire. Our study showed that the extent of foot dorsiflexion, plantar flexion, and inversion at the ankle joint in the treated limb were lower than those in the intact limb. These results partly support our research hypothesis.

According to Roaas, the normal range of motion at the ankle ranges from 5 to 40 degrees for dorsiflexion, from 10 to 55 degrees for plantar flexion, and from 15 to 50 degrees for inversion and eversion [30]. Intra-articular calcaneal fractures continue to pose a challenge for orthopedic surgeons due to the structural complexity of the ankle joint and a high risk of postoperative complications [5,7,8,11–13]. Some authors suggested that restoring the normal structure of the foot may be one of the conditions for restoring normal ankle joint function [5,6,11,12]. On the other hand, some authors reported good functional outcomes without achieving the normal shape of the calcaneus and foot or achieving poor functional outcomes despite successful calcaneal fracture reduction [6,11,13]. Impaired function and mobility at the ankle joint often hinders a return to full performance and may be one of the causes of permanent disability [2,3,6,8]. Therefore, we recommend early rehabilitation with exercises aimed at increasing the range of motion and walking, which accelerates the return to everyday activities and yields more satisfactory outcomes [5,8,18].

There have been no studies assessing the level of physical activity after calcaneal fracture treatment. Some authors assessed the level of physical activity following ankle joint arthrodesis with the Ilizarov method [31] and following derotation corticotomy procedures with the Ilizarov method [32]. They observed good physical activity outcomes after ankle joint arthrodesis with an Ilizarov fixator and after derotation corticotomy procedures with the Ilizarov method [31,32]. Our study showed a significant improvement in UCLA and Grimby activity scores after treatment, which is a good outcome and is similar to those reported in the literature [31,32]. Improved activity scores following treatment with the Ilizarov method may have been related to the patients' ability to ambulate with weight bearing very soon after treatment and with the minimally invasive nature of the surgery [3,5,8].

Schepers et al. assessed 14 patients after open reduction internal fixation and 1 patient after arthrodesis in patients with displaced calcaneal fractures [14]. The median FFI was 18 (interquartile range 6–37), which indicates good activity outcomes after surgery [14]. In another study, 90% of patients after calcaneal fracture treatment were able to resume work [19]. Long-term follow-up by Ibrahim demonstrated no differences between surgically and conservatively treated patients in terms of functional outcomes [20]. The mean FFI was 24.4 in patients treated conservatively and 26.9 in patients treated surgically [20]. Hashemi and his team conducted a retrospective study in which 60 patients with type II intra-articular calcaneal fracture according to the Sanders classification were assessed [21]. All patients underwent open reduction and internal fixation (ORIF) using a lateral approach [21]. Patients were divided into two groups: one with bone allograft and the other without allograft. The study results showed that the average foot function index (FFI) for the entire group of study patients was 9.1. For patients who had a bone allograft, the mean FFI was 9.9, while for those without an allograft it was 5.2. Despite these differences, the statistical analysis did not show significant differences between the groups [21]. In a retrospective study conducted on 416 patients, factors influencing foot function after ankle fracture were assessed [22]. The mean foot function index (FFI) score for all patients was 33.7 [22]. Audet et al.'s analysis showed that body mass index (BMI), smoking, complications, and additional injuries were significant independent predictors of higher FFI scores, indicating poorer foot function [22]. Mastracci and colleagues conducted a prospective study in which 21 patients with calcaneal fractures were evaluated [23]. All patients underwent calcaneal fixation via a sinotarsal approach and completed 12 months of follow-up. In the study group, the average total foot function index (FFI) score was 15 [23]. Furthermore, there was no significant correlation between radiological findings and the total FFI score. This means that although radiological results may indicate proper bone fusion and appropriate anatomy, they do not always translate into better foot function according to the FFI scale [23].

Our patients also noted improved functional scores after treatment, which is consistent with reports by other authors [14,19–23]. Improved general function scores after treatment may be due to increased levels of physical activity and indicate good treatment outcomes. The improvement in functional results after treatment in our patients may be related to the reduction in the incidence of infections and prolonged wound healing associated with the Polish modification of the Ilizarov method in the treatment of calcaneal fractures. Reducing the number of implants in the Polish modification may also reduce pain after treatment, compared to a larger number of implants introduced into the foot by other methods, which also allows for improved function of patients after treatment. The Polish modification of the Ilizarov method in the treatment of calcaneal fractures allows one to achieve functional results similar to those assessed by other authors [14,19–24,31,32].

After calcaneal fracture treatment, the mean range of ankle motion (dorsiflexion and plantar flexion) was 53 degrees, which constituted 88% of its normal value [19]. The mean range of talocalcaneal (i.e., subtalar) joint motion was 20 degrees, which constituted 67% of the normal value [19]. Park et al. evaluated 61 males and 17 females with unilateral calcaneal fracture and were surgically treated with open reduction internal fixation [18]. The authors observed no significant difference in dorsiflexion between the intact limb (16.9°) and the treated limb (16°). However, there were significant differences between the intact and treated limbs in terms of plantar flexion (39.5° vs. 35.3°, respectively) and inversion (50.5° vs. 34.8°, respectively) [18].

In this study, we observed a limited range of motion at the ankle joint following calcaneal fracture treatment with the Ilizarov method. Such limited range of motion may be a result of an insufficiently long or overly restricted rehabilitation regimen and the formation of connective tissue adhesions and scars. Persistent edema and muscle atrophy following surgical treatment of calcaneal fractures are also possible and may also limit joint mobility [7]. Patients who underwent treatment of calcaneal fracture are recommended to undergo a longer and more intense rehabilitation and have periodic follow-up visits to monitor any improvements in ankle mobility. Some of the other authors who evaluated calcaneal fracture treatment reported a limited range of motion in terms of some ankle joint movements following treatment [18,19]. The Polish modification of the Ilizarov method, despite the use of only one Kirschner wire inserted into the foot bones, was associated with limited movement of the ankle joint. The following factors may also have influenced the limited movement of the ankle joint after treatment of calcaneal fractures: concomitant soft tissue injuries after a calcaneal fracture, relatively long immobilization of the ankle joint after a calcaneal fracture, and the possible development of post-traumatic adhesions and fibrosis of soft tissues. Notably, despite limited ankle mobility following treatment in our patients, their level of physical activity and functional scores improved. This may be due to the fact that in order to improve the mobility of the ankle and foot after treatment, the patients started to do more sports and increased their overall physical activity levels.

One limitation of our study is the lack of preoperative assessments in patients with calcaneal fractures. This stems from the fact that such fractures are most often a result of high-energy trauma, which not only typically co-occurs with other injuries but is also impossible to predict in advance [1–3]. Other authors have conducted retrospective analyses of treatment outcomes for calcaneal fractures [3,4,7,8,12,14,18,20] and included patients with concomitant musculoskeletal injuries [5].

Another limitation of our study is the small sample size, which is due to the relatively low incidence of calcaneal fractures, which are most commonly due to traffic accidents and workplace injuries [1–3]. Moreover, some of our patients resided in places located far from our center, which prevented them from returning for follow-up visits. Nonetheless, other studies assessing calcaneal fracture treatment also included small study populations [3,4,8,12,14,16].

The strengths of our study are the use of homogeneous surgery and rehabilitation protocols and the fact that all procedures were conducted by the same orthopedic surgeon. In the future, we are planning to expand this study by using a larger group of patients and extending the follow-up period.

5. Conclusions

The treatment of calcaneal fractures with the use of a Polish modification of the Ilizarov method helps achieve satisfactory functional outcomes.

Patients with calcaneal fractures treated with the Ilizarov method are recommended to have a longer and more intensive rehabilitation.

The range of ankle motion in the treated limb was limited in comparison with that in the intact limb; however, this did not greatly affect the patients' return to their earlier, pre-injury level of physical activity.

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Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki, and approved by the Bioethics Committee of the University of Opole (protocol code UO/0023/KB/2023) and date of approval 26 October 2023.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

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Gait assessment in patients with intra-articular calcaneal fractures after treatment with the Ilizarov method

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ABSTRACT

Background: Intra-articular and comminuted fractures of the calcaneus constitute a significant orthopedic challenge. Calcaneal fracture management should primarily aim to achieve good clinical and biomechanical outcomes, pain reduction, and normal function following treatment.
Research question: How does Ilizarov treatment of calcaneal fractures affect gait parameters?
Methods: This retrospective study included 21patients (7 women, 14 men) who were treated for intra-articular calcaneal fractures with the Ilizarov method in the period 2021–2022. Nineteen healthy volunteers constituted the control group. Gait assessments were conducted with a BTS G-SENSOR device (BTS Bioengineering Corp., Quincy, MA, USA). The gait assessment evaluated the following parameters: assessment duration expressed in seconds (s), cadence expressed as the number of steps per minute (steps/min), gait velocity (m/s), stride length (m), stance phase (%), swing phase (%), double support phase (%), and single support phase (%). The study assessed pain intensity in the VAS scale, *Böhler*'s angle and *Gissane's* angle.
Results and Significance: We observed no significant differences between the experimental group and the healthy control group in terms of cadence, gait velocity, or stride length. Patients in experimental group showed significantly shortened stance and single support phases in the treated limb in comparison with those in the intact limb; the remaining gait parameters were similar in the treated and intact limb. We observed no significant differences between the treated limbs in the patient group and the nondominant limbs in the control group in terms of any gait parameters. In the follow-up, the average pain value on the VAS scale was 2.3. The median Böhler angle changed from 5.5° preoperatively to 28.5° postoperatively, $p < 0.001$. The median Gissane's angle was 119° before surgery and 143° after surgery, $p < 0.001$.The use of the Ilizarov method in the treatment of calcaneal fractures helps achieve sufficient normalization of most gait parameters, with their values similar to those observed in healthy volunteers. After treatment of calcaneal fractures using the Ilizarov method, radiological parameters improved. The biomechanical outcomes of calcaneal fracture treatment with the Ilizarov method are good.

Introduction

Intra-articular and comminuted fractures of the calcaneus constitute a significant orthopedic challenge [1–13]. These fracture types require surgical treatment. In the case of intra-articular fractures there continue to be divided opinions as to the optimal treatment selection and limiting potential complications [1,3,5,6]. Well-established methods of treating intra-articular and comminuted calcaneal fractures are open reduction and internal fixation (ORIF) with a plate or screws and fracture reduction and fixation with the Ilizarov method [1–13].

The calcaneus plays a crucial role in normal gait [2,7,9,12–18]. The irregular shape and complex biomechanics of the calcaneus and the

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adjacent tarsal bones poses a challenge in reconstructing the normal anatomical shape of the calcaneus and its articular surfaces, which relatively often leads to unsatisfactory treatment outcomes [4]. The changes in calcaneal structure and the spatial arrangement of its articular surfaces may considerably alter normal gait biomechanics and accelerate the development of degenerative changes [1,7]. The subtalar joint is involved in intra-articular calcaneal fractures, so any post-operative effect to subtalar eversion/inversion may have an impact on gait parameters.

The natural shape and structural integrity of the calcaneus and the foot determines normal biomechanical parameters of the lower limbs, including gait parameters [2,7,9,12–18]. Calcaneal fracture management should primarily aim to achieve good clinical outcomes, pain reduction, and normal function following treatment [5,7,9,12,13]. Normal gait parameters demonstrate good treatment outcomes of musculoskeletal disorders [2,9,13–20]

One of the surgical treatment methods used in the treatment of calcaneal fractures is the Ilizarov method [1,4–7,9,10]. Gait assessments play an important role in clinical practice, since they help monitor the progress of rehabilitation throughout the postoperative period [2, 14–18,21]. A G-Sensor device offers objective, repeatable, and reproducible assessments of gait parameters [14,19,22–25].

There have been no studies to assess gait parameters following calcaneal fracture treatment with the Ilizarov method. Previous studies focused on assessing gait following ORIF of calcaneal fractures with the use of plates [2,15–18]. The authors of those studies reported worse gait parameters in the treated limb than in the intact limb and worse biomechanical parameters in comparison with those in a healthy control group [2,15,16,18].

We posed a hypothesis that the use of the Ilizarov method in calcaneal fracture treatment would help restore normal biomechanical spatiotemporal parameters of gait in patients after surgery.

Our research goal was a detailed analysis of spatiotemporal gait parameters in patients with a calcaneal fracture treated with the Ilizarov method (in which patients the shape of the calcaneus was approximately recreated, without full anatomy of the calcaneus), and subsequent comparison of the results with those of a control group.

Materials and methods

This retrospective study included patients who were treated for intra-articular calcaneal fractures with a Polish modification of the Ilizarov method in the period 2021–2022. The study inclusion criteria included intra-articular calcaneal fracture treatment with a Polish modification of the Ilizarov method [7,9], a minimum 2-year follow-up, complete medical and radiological records, complete gait assessment results, the patient's informed consent, no associated lower limb injuries and an absence of lower limb comorbidities. All patients were treated by the same orthopedic surgeon.

Individuals who did not meet the above criteria were excluded from the study. Prior to study inclusion, all patients had been informed of a voluntary nature of their participation and the possibility of withdrawing from the study at any time. The study had been approved by a local ethics committee (UO/0023/KB/2023).

All patients from the experimental group underwent a closed reduction with a Polish modification of the Ilizarov method [7,9], Figs. 1–3. The modified Ilizarov external fixator consisted of two rings, fixed to crural bones with Kirschner wires, and one-half-ring, fixed to the calcaneus with one Kirschner wire. The distal leg ring was attached to the calcaneal semi-ring with two connectors. The connectors are two threaded rods, attached perpendicularly to each other, enabling distraction and dorsal reposition of the calcaneal bone fragments (Figs. 1 and 3). The procedure was performed in a supine position, under spinal anesthesia. First, two rings were attached with Kirschner wires to the tibia and fibula. For better stabilization, each of the Kirschner wires attached to both rings passed through the tibia, and one Kirschner wire attached to both rings passed through the fibula. Subsequently, one 2-mm Kirschner wire was inserted (under fluoroscopy) from the medial to the lateral side, into the calcaneal tuberosity, into the most proximal and posterior bone fragment (Figs. 1 and 3). Then, a calcaneal semi-ring was attached to the Kirschner wire inserted into the calcaneus. The next step of the procedure involved joining the calcaneal semi-ring with the distal leg ring with two connectors (two perpendicular, threaded rods). Then, calcaneal fracture reduction was performed, under fluoroscopy, along the connectors between the calcaneal semi-ring and the distal leg ring (bone fragment distraction in long axis and dorsal repositioning were performed). Bone fragments were repositioned via closed reduction, under fluoroscopy, without opening the site surgically. This modified spatial arrangement of an Ilizarov external fixator and the effect of ligamentotaxis, enabled an indirect correction of calcaneal bone fragment positioning. Thanks to an indirect alignment of calcaneal bone fragments in a sagittal plane, the modified arrangement of the fixator also enables the correction of a varus or valgus position of calcaneal bone fragments (distraction or compression in a sagittal plane along one connector only).

Fig. 1. The model of an Ilizarov fixator used for calcaneal fracture treatment.

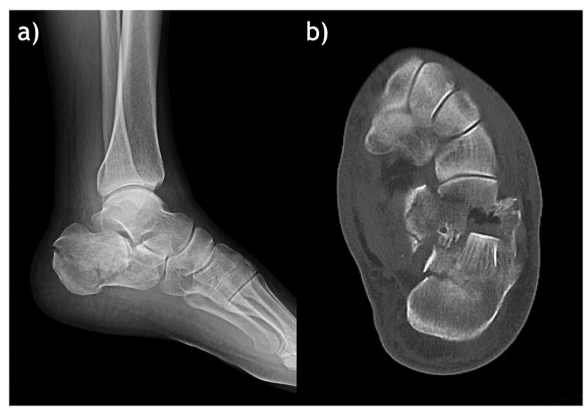

Fig. 2. The patient before treatment, (a) lateral X-ray, CT scan (b).

Radiological assessment of the repositioning of bone fragments and the quality of articular reduction was performed on the basis of X-ray images of the foot and ankle in the lateral and frontal views, as well as

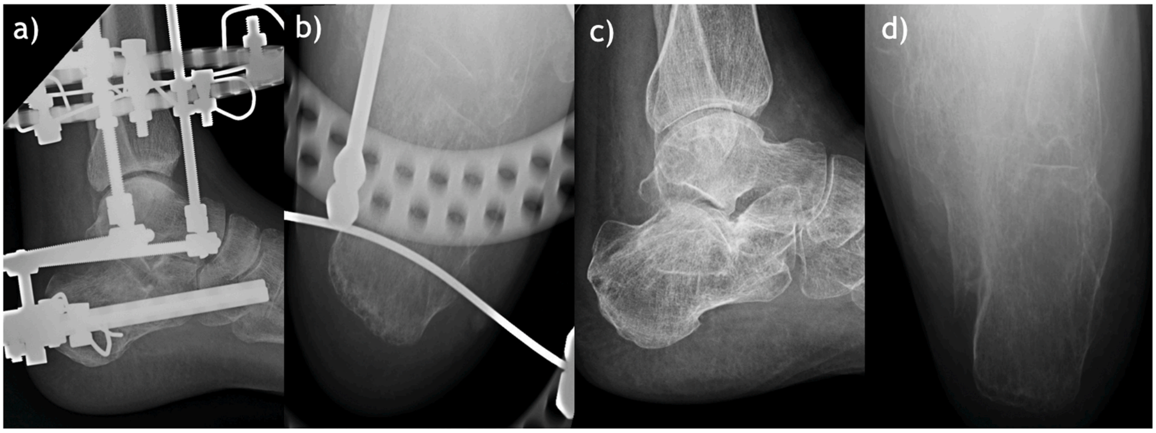

Fig. 3. The patient during (a,b), and after (c,d) treatment of a intra-articular calcaneal fracture with the Polish modification of the Ilizarov method.

axial images of the heel. Radiological follow-ups were performed postoperatively and periodically in outpatient follow-ups. Rehabilitation was conducted following the same protocol. On postoperative day one, the patients began walking with the use of two elbow crutches and partial weight bearing. The load on the treated limb was gradually increased, adjusting it to the patients' pain tolerance. Treatment progress was assessed at follow-up outpatient visits; and the fixator was removed once bone union was confirmed clinically and radiologically.

Subjects

The inclusion and exclusion criteria helped select 21 patients (7 women, 14 men), aged between 25 and 67 years (mean age 47 years), with the body mass index (BMI) ranging from 24 to 40 (mean 28), height of 152–188 cm (mean 171 cm), weight of 61–130 kg (mean 81 kg). Two patients from the evaluated group had open fractures. Nineteen healthy volunteers constituted the control group, which was meticulously matched with respect to sex and showed significant differences in terms of age or BMI. The experimental group was stratified according to the Sanders classification, which yielded three type II fractures, five type III fractures, and 13 type IV fractures. The maintenance period of the Ilizarov fixator was on average 88 days (67–105 days).

Protocol of gait analysis

Gait assessments were conducted with a BTS G-SENSOR device (BTS Bioengineering Corp., Quincy, MA, USA) equipped with an advanced triaxial accelerometer with multiple levels of sensitivity (±2, ±4, ±8, ±16 g), triaxial magnetic field sensor, gyroscope with adjustable sensitivity (±300°/s, ±1200°/s), and a GPS module. This compact (70 × 40 × 18 mm [length×width×height]), light-weight (37 g) devise yields accurate measurements. Data acquisition frequency was up to 100 Hz; subsequently, the measurements were wirelessly transmitted to a computer via Bluetooth and processed with dedicated BTS G-Studio software. The software helps calculate spatiotemporal gait parameters and the percentage of their similarity between the two limbs.

All subjects received detailed instructions on the measurement procedure, and their body weight and height were measured. Then, each subject was fitted with a wireless BTS G-SENSOR measuring device, secured with a semi-elastic belt at the level of the fifth lumbar (L5) vertebra, Fig. 4. The G-Sensor is suitable for gait assessment, as demonstrated by the coefficient of variation between instruments 2.5 % and the inter-instrument correlation coefficient from 0.90 to 0.99 [26,27]. The G-sensor provides an objective, accurate, and reproducible assessment of all phases of the gait cycle and helps detect potential deviations from normal gait parameters [14,19,22–25].

Study assessments were conducted according to the WALK protocol, starting with a brief period of motionlessness to allow for automatic sensor stabilization followed by walking the distance of 8 m in a straight line, turning back and returning to the starting point. The assessments were done barefoot, and the assessed individuals covered the assigned distance walking naturally at their own, steady pace. Each individual underwent three measurements, with their mean value used for further analyses. The assessment results were transferred into BTS G-STUDIO software designed to process data and calculate spatiotemporal gait

Fig. 4. A G-sensor fitted onto the patient's body with an elastic belt.

parameters and the rates of their similarity in the two lower limbs.

The gait assessment evaluated the following parameters: assessment duration expressed in seconds (s), cadence expressed as the number of steps per minute (steps/min), gait velocity (m/s), stride length (m), stance phase (%), swing phase (%), double support phase (%), and single support phase (%).

The treated and intact lower limbs of patients with calcaneal fractures were compared in terms of their biomechanical parameters. We also compared the biomechanical parameters obtained in the group of patients with calcaneal fractures treated with the Ilizarov method with those obtained in the control group of healthy volunteers; this included comparing the intact limbs in the experimental group with the dominant limbs in the control group and the treated limbs in the experimental group with the nondominant limbs in the control group.

Pain severity was assessed with a 10-point visual analog scale (VAS).

In the radiological evaluation, Böhler's angle and Gissane's angle were analyzed before surgery and in the long-term follow-up.

Statistical analysis

Data were statistically analyzed using Statistica 13.1. The Shapiro–Wilk test was used to check for normality of distribution. Student's *t*-test was used to compare quantitative variables. The level of statistical significance was set at $p < 0.05$

Results

The treated patients and the control group showed no significant differences in such spatiotemporal gait parameters as cadence, gait velocity, and stride length (Table 1).

The evaluated patient group showed a shortened stance phase of the treated limb (59 %) in comparison with that of the intact limb (64 %) ($p = 0.043$), (Table 2 and Fig. 5). There was also a significantly shortened single support phase, which was 36 % in the treated limb and 42 % in the intact limb ($p = 0.025$) (Table 2 and Fig. 6). Other gait parameters were not significantly different between the treated and the intact limbs (Table 2).

There were no significant differences between the control and experimental group in terms of most of the evaluated parameters, except for the following two (Table 3). The stance phase of the intact limb in the experimental group was significantly prolonged at 64 % in comparison with that in the dominant limb in the control group (60 %) ($p = 0.013$), (Table 3 and Fig. 7). Moreover, the swing phase in the intact limb in patients was shortened at 36 % in comparison with that in the dominant limb in controls (40 %) ($p = 0.02$), (Table 3 and Fig. 8).

In the follow-up, the average pain value on the VAS scale was 2.3 (from 0 to 6).

The median Böhler angle changed from 5.5° preoperatively to 28.5° postoperatively, $p < 0.001$. The median Gissane's angle was 119° before surgery and 143° after surgery, $p < 0.001$.

Discussion

In this study, we assessed gait parameters in patients with intra-articular calcaneal fractures treated with a Polish modification of the Ilizarov fixator. We observed normalization of most post-treatment gait parameters, which supports our research hypothesis. We observed no significant differences between the experimental group and the healthy control group in terms of cadence, gait velocity, or stride length. Patients in experimental group showed significantly shortened stance and single support phases in the treated limb in comparison with those in the intact limb; the remaining gait parameters were similar in the treated and intact limb. We observed no significant differences between the treated limbs in the patient group and the nondominant limbs in the control

Table 1
Selected gait parameters in Patients group and Control group.

Analyzed variable	Group		p value*
	Patients	Control	
	mean±standard deviation		
analysis duration (s)	67.03±26.17	53±33.77	0.315
cadence (steps/min)	97.28±8.28	90.81±13.01	0.209
velocity (m/s)	1.02±0.26	0.83±0.21	0.075
step length (m)	0.63±0.12	0.54±0.07	0.055

* Student's *t*-test.

Table 2
Spatio-temporal parameters of gait in Patients group after treatment.

Analyzed variable	OL	NOL	p value*
	mean±standard deviation		
gait cycle duration (s)	1.27±0.08	1.26±0.07	0.760
step length (%)	50.95±3.42	49.04±3.42	0.254
support phase duration (%)	59.18±5.27	64.13±4.24	0.043
swing phase duration (%)	40.81±5.27	36.07±4.56	0.058
double support duration (%)	11.81±2.61	10.74±2.83	0.416
single support duration (%)	36.14±4.58	41.57±4.71	0.025
steps analysed	14.11±8.97	13.77±7.49	0.933

OL - operated limb, NOL - non-operated limb.
* Student's *t*-test.

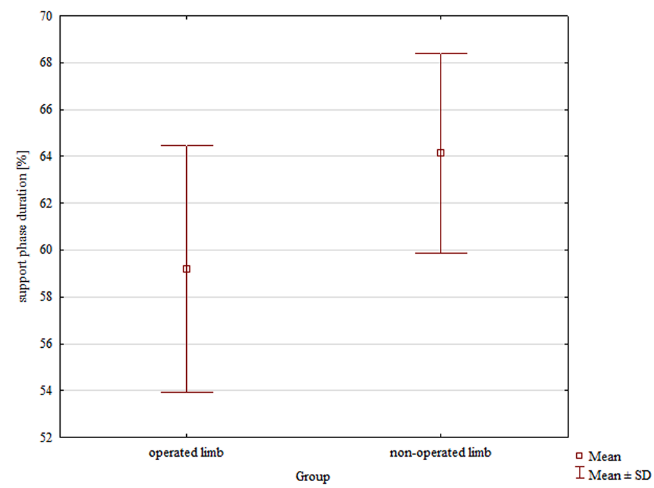

Fig. 5. Support phase duration in the treated and non-treated lower limb in patients after surgery.

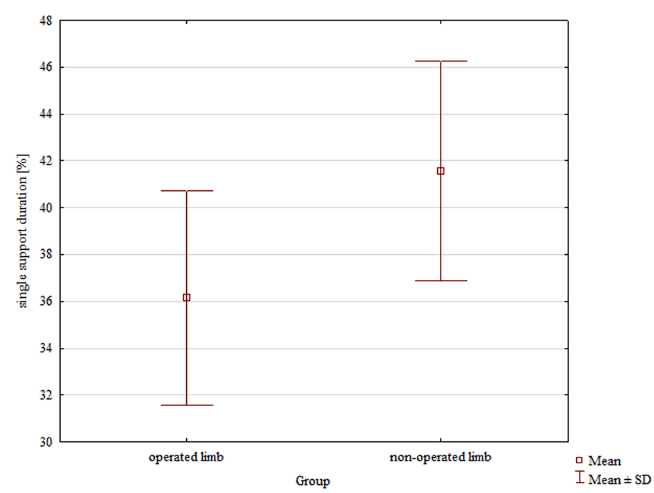

Fig. 6. Single support phase duration in the treated and non-treated lower limb in patients after surgery.

Table 3
Detailed gait parameters in Patients group and Control group.

Analyzed variable	Group		p value*
	Patients	Control	
	mean±standard deviation		
gait cycle duration OL (s)	1.27±0.08	1.37±0.23	0.238
step length OL (%)	50.95±3.42	48.61±3.29	0.129
support phase duration OL (%)	59.18±5.27	61.68±2.71	0.171
swing phase duration OL (%)	40.81±5.27	38.31±2.71	0.171
double support duration OL (%)	11.81±2.61	10.48±2.64	0.264
single support duration OL (%)	36.14±4.58	39.39±3.71	0.088
steps analysed OL	14.11±8.97	11.83±10.07	0.598
gait cycle duration NOL (s)	1.26±0.07	1.39±0.23	0.146
step length NOL (%)	49.04±3.42	51.39±3.29	0.129
support phase duration NOL (%)	64.13±4.24	59.51±3.52	0.013
swing phase duration NOL (%)	36.07±4.56	40.49±3.52	0.021
double support duration NOL (%)	10.74±2.83	11.39±2.39	0.576
single support duration NOL (%)	41.57±4.71	38.24±2.64	0.053
steps analysed NOL	13.77±7.49	10.83±8.27	0.411

* Student's *t*-test.

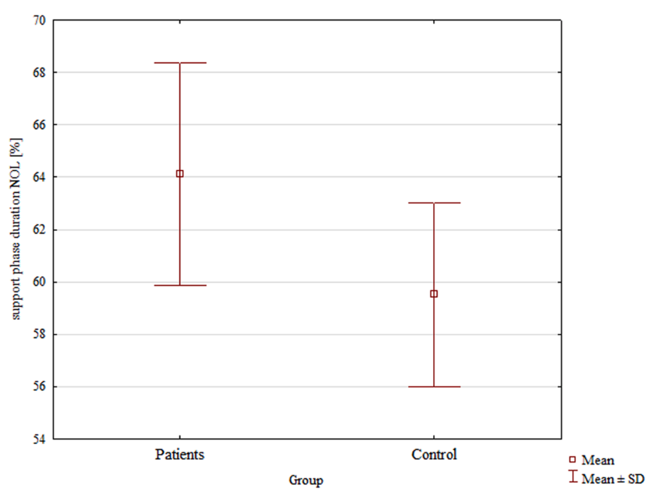

Fig. 7. Support phase duration in the non-treated limb in the experimental group and the dominant limb in the control group.

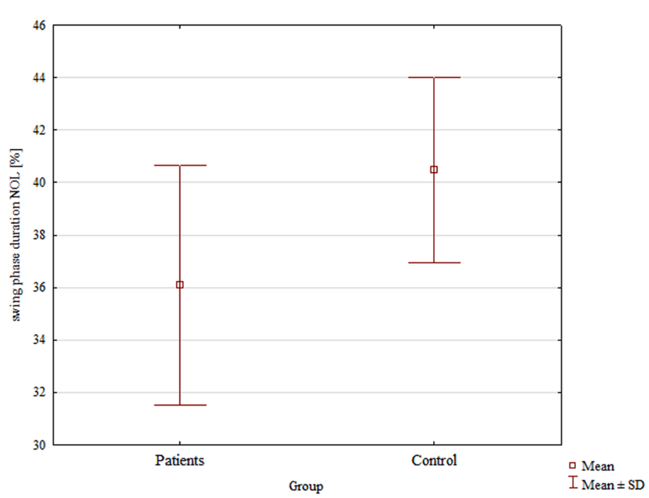

Fig. 8. Swing phase duration in the non-treated limb in the experimental group and the.

group in terms of any gait parameters.

The purpose of surgical treatment in cases of calcaneal fracture is to restore the normal anatomical structure of the calcaneus and its articular surfaces, which poses a considerable challenge for many orthopedic surgeons, but as some researchers believe, probably is key to restoring normal gait biomechanics and reducing pain [1,5,7–10,19]. The subtalar joint is involved in intra-articular calcaneal fractures, therefore abnormal mobility and shape of the subtalar joint after injury may affect gait parameters.

The idea of the Polish modification of the Ilizarov method in the treatment of calcaneal fractures is low invasiveness (no open surgical access, only 1 Kirschner wire in the foot). In our method of treating calcaneal fractures, we do not strive for a perfectly anatomical reconstruction of the articular surfaces. Some authors reported positive outcomes in the treatment of calcaneal fractures despite incomplete fracture reduction [8], whereas other studies showed no satisfactory clinical effects despite good radiological outcomes [5]. We believe that the approximate shape of the calcaneus should be recreated and that no efforts should be made to obtain the full anatomy of the calcaneus.

Ensuring normal range of motion and reducing pain after surgical treatment are key aspects of the restoring full functionality and normal patterns of movement [2,9,14,15,17,28,29–31]. Joint mobility after calcaneal fracture treatment with ORIF was reported to correlate with bone fragment displacement on radiological follow-up [2]. Analyzing the biomechanics of motion in conjunction with performing clinical and radiological assessments helps evaluate treatment outcomes in various types of musculoskeletal dysfunction [2,14–18,20,28–31]. Previous studies assessed the biomechanics of gait following calcaneal fracture treatment with ORIF with a plate [2,15–18]. However, there have been no studies aiming to assess gait parameters following calcaneal fracture treatment with the Ilizarov method.

Hoeve et al. assessed selected parameters of gait in 13 patients with calcaneal fracture treatment with ORIF [2]. Those authors observed slower velocity and limited flexion-extension movements in patients after calcaneal fracture treatment in comparison with those in a healthy control group [2]. A different study assessed ground reaction forces in 13 patients with calcaneal fractures treated with ORIF [16]. That study showed lower minimum force during midstance and lower maximum force during toe-off in the ORIF group than in the healthy control group [16]. Brand observed an improvement in some gait parameters following ORIF of calcaneal fractures when comparing the results at 3 and 6 months after treatment [17]. Jandova et al. noted differences in loading and temporal variables between the treated and intact limbs of 22 patients after calcaneal fracture treatment with ORIF [15]. Another study, which assessed gait with a pedobarographic platform in 28 patients after calcaneal fracture treatment with ORIF, demonstrated considerable reduction in maximum pressure and lateralization of hindfoot pressure in the treated limb in comparison with the intact limb [18].

Wietecki et al. assessed gait parameters in 23 patients with pilon fractures treated with the Ilizarov method [31]. Those authors observed limited ankle inversion, dorsiflexion, and abduction in the treated limb when compared with those movements in the intact limb [31]. Canseco et al. assessed gait parameters in a group of 15 patients who had undergone intramedullary nail insertion due to tibial shaft fracture [20]. That study showed slower gait velocity with shorter stride length and lower cadence in the patients after surgery than in the healthy control group. Moreover, the stance phase of the gait cycle was shorter in the patients [20]. Follow-up evaluation of 22 patients treated surgically due to symptomatic planovalgus foot showed improvement in the form of increased gait velocity and cadence and a shortened gait cycle in comparison with the preoperative values [14].

According to Perry the stance phase should constitute 60 % and the swing phase 40 % of the gait cycle [24]. In our study, we observed the stance phase and the single support phase in the treated limb shortened to 59 % and 36 %, respectively, in comparison with those in the intact limb, at 64 % and 42 %, respectively. The discrepancy between the lower limbs in terms of spatiotemporal parameters indicates worse gait normalization in patients after calcaneal surgery with the Polish modification of the Ilizarov method.

We also observed the stance phase in the non-treated limb in the patient group to be significantly prolonged at 64 % in comparison with that in the dominant limb in the control group (60 %). We also observed the swing phase in the non-treated foot to be shortened at 36 % in comparison with that in the dominant limb in the control group (40 %). Supposedly, the compensatory and adaptive mechanisms in the evaluated patients tend to reestablish a functional symmetry in gait. A symmetrical dysfunction is more beneficial than an asymmetrical one from the biological and biomechanical perspective. These dysfunctions may be due to several factors: persistent soft-tissue edema in some patients, reduced muscle strength, and reduced Achilles tendon capacity due to trauma or chronic immobilization in some patients [17,18]. Patients with calcaneal fractures treated with the Ilizarov method may require longer and more intense rehabilitation.

It is worth noting that our study showed no significant differences in gait velocity, cadence, or stride length between the experimental and control group, which indicates a restored lower limb function after surgery. Moreover, the treated and the non-treated limb did not differ in most of the analyzed gait parameters. We observed no differences in biomechanics between the treated limb in calcaneal fracture patients and the nondominant limb in healthy controls. The results of our study showed improved gait parameters following calcaneal fracture treatment with the Ilizarov method. This indicates that the level of treated limb function achieved in patients with calcaneal fractures treated with the Ilizarov method was similar to that in the healthy control group.

One of the limitations of our study was its retrospective nature, which was due to the impossibility of assessing gait parameters in patients prior to surgery. Calcaneal fractures result from high-energy trauma, cause pain, and limit mobility in the ankle joint making it impossible to conduct gait assessments prior to the intervention. Notably, retrospective studies are common in the literature on calcaneal fracture treatment [1,2,6,7,9,15–18]. Another limitation of our study is the relatively small sample size, which is due to the fact that calcaneal fractures are relatively rare, constituting 2 % of all fractures. Moreover, the calcaneal injuries were often incurred at the workplace, which resulted in some of the patients leaving the region where the study was conducted to travel back home after undergoing surgery. This considerably limited the possibility of long-term follow-up, particularly to assess gait parameters. Other authors also conducted comparisons in study groups of the size similar to that in our study [1,2,6,7,9,10,14,16,31]. This manuscript assesses selected gait parameters. In subsequent works prepared for publication, we evaluate a similar group of patients in terms of clinical and radiological parameters. Patients who have calcaneal fracture may develop abnormal pressure points of the foot [16,18]. In our study, we did not assess the parameters of foot load distribution in terms of value and location, which is also a limitation. In the future, we also plan to evaluate ground reaction forces and other force parameters in a similar group of patients. In the future, we plan to perform a study comparing gait parameters in patients after treatment of calcaneal fractures with the Ilizarov method and ORIF with plate stabilization.

One strength of our study was the use of a consistent surgical and rehabilitation protocol, all surgeries being performed by the same orthopedic surgeon, and gait function being assessed by the same specialist. In the future, we are planning to expand this study to include more patients and have a longer follow-up.

Brand is of the opinion that gait velocity after a calcaneal fracture may be lower due to the development of degenerative changes [17]. In our study we did not observe a lowering of gait velocity in patients with calcaneal fractures after treatment, which lets us suspect that the development of degenerative changes in our patients was not advanced.

Some authors reported that calcaneal fracture treatment may be followed by alterations in the shape of the calcaneus and the foot, limited joint mobility, and arthrosis, which may lead to gait abnormalities and long-term use of braces and orthotic devices [12,15,17,18]. Most of the gait parameters we assessed in patients had similar values to those obtained from the healthy control group, which suggests that calcaneal and foot deformities and joint mobility limitations were largely averted in our patients.

In the patients we evaluated, radiological parameters such as Böhler's angle and Gissane's angle improved after treatment. After treatment, our patients recorded an average pain score of 2.3 on the VAS scale, which indicates a low intensity of pain. Treatment of intra-articular calcaneal fractures using the Polish modification of the Ilizarov method allows for improvement of radiological parameters and reduces pain after treatment.

Conclusion

The G-sensor is a useful tool in assessing gait parameters in patients with calcaneal fractures treated with the Ilizarov method.

Our results show that the approximate shape of the calcaneus should be recreated and that no efforts should be made to obtain the full anatomy of the calcaneus.

The use of the Ilizarov method in the treatment of calcaneal fractures helps achieve sufficient normalization of most gait parameters, with their values similar to those observed in healthy volunteers.

We did not observe differences in cadence, gait velocity, or stride length between the group of patients and the group of healthy controls.

After treatment of calcaneal fractures using the Ilizarov method, radiological parameters improved.

The biomechanical outcomes of calcaneal fracture treatment with the Ilizarov method are good.

CRediT authorship contribution statement

Marcin Pelc: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Władysław Hryniuk:** Investigation, Data curation. **Andrzej Bobiński:** Methodology, Investigation, Data curation. **Joanna Kochańska-Bieri:** Writing – original draft, Resources. **Łukasz Tomczyk:** Writing – original draft, Software, Resources, Methodology. **Daniele Pili:** Writing – original draft, Resources. **Piotr Morasiewicz:** Writing – review & editing, Writing – original draft, Methodology, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

There was no conflict of interest.

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Ethics statement

Prior to study inclusion, all patients had been informed of a voluntary nature of their participation and the possibility of withdrawing from the study at any time. The study had been approved by a local ethics committee (UO/0023/KB/2023).

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Original papers

AHEAD OF PRINT

Clinical and radiological assessment of the Polish modification of the Ilizarov external fixator for the treatment of intra-articular calcaneal fractures

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A – research concept and design; B – collection and/or assembly of data; C – data analysis and interpretation; D – writing the article; E – critical revision of the article; F – final approval of the article

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Abstract

Background. There is currently no established gold standard for the treatment of calcaneal fractures.

Objectives. To conduct a clinical and radiological evaluation of patients following intra-articular calcaneal fractures treated with the Polish modification of the Ilizarov method.

Materials and methods. This was a 2-center retrospective study. We evaluated 27 patients (2 women and 25 men) aged 28–73 years (mean age 50.5 years) after treatment of intra-articular calcaneal fractures with the Polish modification of the Ilizarov method. We assessed pain using a visual analogue scale (VAS), American Orthopedic Foot and Ankle Society (AOFAS) scores, patient satisfaction with treatment, use of analgesics, duration of Ilizarov treatment, length of hospital stay, duration of surgery, patient's declared willingness to choose the same treatment again, complications, degenerative changes, Böhler angle, inflection angle, and Gissane angle.

Results. The mean follow-up period was 3 years and 2 months. Following treatment, the mean VAS pain score was 2.3. Prior to surgery, all patients were taking analgesics in comparison with only 2 patients (7.4%) at long-term follow-up. The treatment was rated as satisfactory by 11 patients, with 16 patients rating it as highly satisfactory. The mean post-treatment AOFAS score was 76.6 points. The Ilizarov fixator was removed after a mean period of 88 days. The mean duration of hospital stay was 7.4 days. The mean duration of the procedure was 44 min. All patients would choose the same treatment again. Complications were observed in 5 patients. The long-term follow-up visit revealed degenerative changes in the talocalcaneal joint in 8 patients. The median Böhler angle was 5.5° preoperatively and 28.5° postoperatively, $p < 0.001$. The median preoperative inflection angle of 160° decreased to 145°, $p < 0.001$. The median preoperative Gissane's angle of 119° increased significantly to a median postoperative value of 143°, $p < 0.001$.

Conclusions. The patients achieved good clinical and radiological outcomes.

Key words: external fixator, Ilizarov method, radiological assessment, clinical assessment, calcaneal fractures

Background

Calcaneal fractures account for 1–2% of all fractures.[1–4] These fractures are predominantly intra-articular and displaced (75%).[1,4] Comminuted and intra-articular calcaneal fractures have been a serious orthopedic challenge for years.[1–13] There is no gold standard for the treatment of fractures of this type.[1–4,6,7,10–13]

The development of external fixation devices, particularly the Ilizarov method, enabled their use in the treatment of calcaneal fractures, even comminuted and/or intra-articular ones.[2–4,6–15] The use of the Ilizarov method in calcaneal fracture management has been reported to yield good outcomes, often even better than those achieved with internal fixation.[2,6] However, most authors who used the Ilizarov method did it with an open access approach to reducing the calcaneal fracture, which may have been responsible for complications in the form of infections, delayed wound healing, or skin and soft tissue necrosis.[2,3,6–10,12,13]

The Polish modification of the Ilizarov method enables closed reduction and fixation of the calcaneal bone fragments without an open access approach and allows stabilization of the foot with only 1 Kirschner wire.[4,15] There is only 1 study presenting the clinical and radiological results of closed reduction and Ilizarov fixation of calcaneal fractures with 1 Kirschner wire.[4] The authors of that paper evaluated 11 patients with calcaneal fractures treated with the Ilizarov method and analyzed selected clinical and radiological parameters (Rowe's score, Olerud–Molander Ankle score, Böhler angle, inflection angle).[4] Both the clinical and radiological parameters improved after treatment.[4] In another article, the authors assessed the balance and load distribution of the lower limbs after treatment of calcaneal fractures using the modified Ilizarov method.[15]

Those who have analyzed the treatment outcomes following calcaneal fracture management with the Ilizarov method usually assessed only selected clinical and radiological parameters.[2,3,6,9,13]

The reported peri-implant infection rates following calcaneal fracture treatment with the Ilizarov method were 16–33%.[2,3,6,10,12] There have also been reports of degenerative changes developing after this treatment; however, the authors did not assess the exact rates.[3,4]

We proposed the hypothesis that the Polish modification of the Ilizarov external fixator may help achieve good outcomes in the treatment of calcaneal fractures.

Objectives

The purpose of our study was to conduct a comprehensive clinical and radiological evaluation of patients following intra-articular calcaneal fractures treated with the Polish modification of the Ilizarov method.

Materials and methods

Study design

Our study was retrospective in nature. Thirty patients with intra-articular calcaneal fractures were treated with the Polish modification of the Ilizarov method (Fig. 1,2) in the years 2018–2021 in 2 academic level I trauma centers.

Fig. 1. The patient before treatment on (A) lateral X-ray and (B) computed tomography (CT) scan

Participants

The study inclusion criteria were a Sanders type II, III or IV calcaneal fracture treated with the Polish modification of the Ilizarov method, patient consent to participate in the study, complete medical and radiological records, a follow-up period of over 2 years, and no lower limb comorbidities. The exclusion criteria were a follow-up period under 2 years, incomplete medical records and incomplete radiological records. All patients were informed of the voluntary nature of their participation in this study. The study was approved by the Bioethics Committee of the University of Opole, Poland (protocol code UO/0023/KB/2023).

Interventions

All patients were diagnosed with a calcaneal fracture based on X-rays (anteroposterior and lateral views and the calcaneal axial view) and computed tomography (CT). The analyzed cases included 4 Sanders type II, 6 Sanders type III and 17 Sanders type IV calcaneal fractures. On arrival to the emergency room, all fractures were initially immobilized in a short leg cast. In the case of compound fractures (3 in the study population), the wounds were thoroughly rinsed, revised, cleaned, and sutured, and the limb was immobilized in a short leg cast on day 1. Patients with compound fractures received antibiotic therapy (600 mg clindamycin 3 times a day for 14 days, administered intravenously in the ward and orally for outpatient treatment). Fracture reduction and fixation with the Ilizarov method

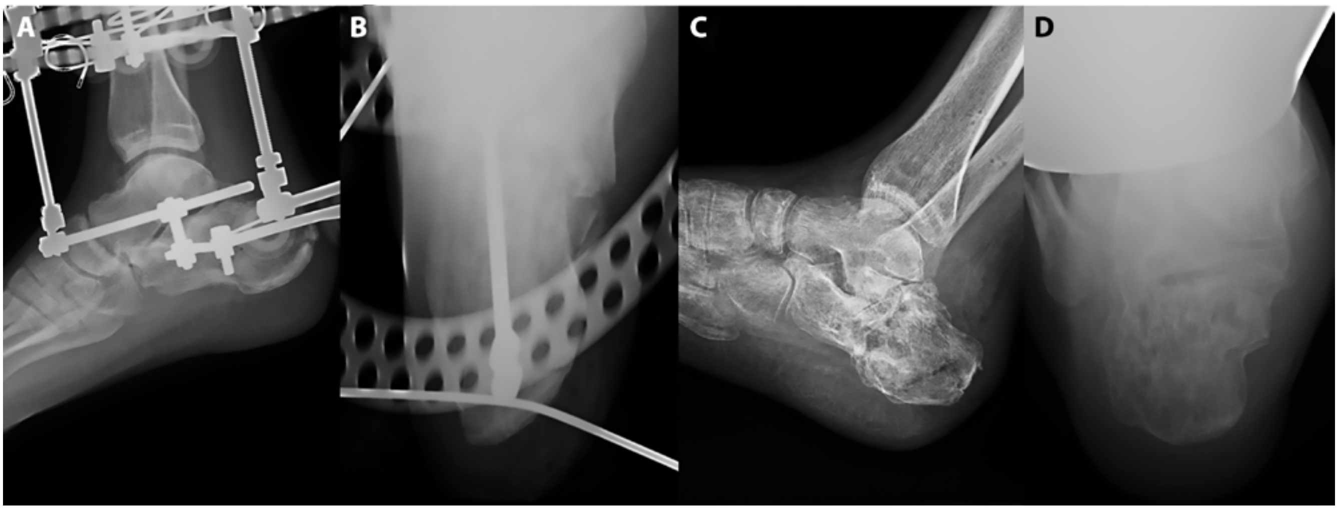

Fig. 2. The patient during (A, B), and after (C, D) treatment of an intra-articular calcaneal fracture with the Polish modification of the Ilizarov method

were conducted on days 3–5 after injury, depending on operating room and operator availability (all patients were operated on by the same orthopedic surgeon). Patients received perioperative antibiotic prophylaxis in the form of 1 dose of Biofazolin (1 g; BIOTON, Warsaw, Poland) administered intravenously.

The Polish modification of the Ilizarov external fixator was introduced for the treatment of calcaneal fractures in Wrocław, Poland, in the 1990s,[4,15] and personal communication: P. Koprowski and L. Morasiewicz. This modified external fixator comprised 2 rings, each fixed to the tibia and fibula with 2 or 3 Kirschner wires, and a semi-ring fixed with a single Kirschner wire inserted into the calcaneus (Fig. 3). The distal leg ring was attached to the calcaneal semi-ring with 2 connectors. The connectors were 2 threaded rods, attached perpendicularly to each other, enabling distraction and dorsal reposition of the calcaneal bone fragments (Fig. 3).

The procedure was performed in the supine position under spinal anesthesia. First, the 2 rings were attached with Kirschner wires to the tibia and fibula. Subsequently, a 2-mm Kirschner wire was inserted (under fluoroscopy) medially into the calcaneal tuberosity and into the most proximal and posterior bone fragment (Fig. 3). Then, a calcaneal semi-ring was attached to the Kirschner wire inserted into the calcaneus. The next step of the procedure involved joining the calcaneal semi-ring with the distal leg ring with 2 connectors (2 perpendicular threaded rods). Then, calcaneal fracture reduction was performed, under fluoroscopy, along the connectors between the calcaneal semi-ring and the distal leg ring (bone fragment distraction and dorsal repositioning were performed). The bone fragments were repositioned via closed reduction, under fluoroscopy, without opening the site surgically. This modified spatial arrangement of an Ilizarov external fixator and the effect of ligamentotaxis enabled an indirect correction of the calcaneal bone fragment's positioning. Thanks to an indirect alignment of the calcaneal bone fragments in the sagittal plane, the modified arrangement of the fixator also enables the correction of the varus or valgus position of the calcaneal bone fragments (distraction or compression in the sagittal plane along 1 connector only).

Fig. 3. The Polish modification of the Ilizarov external fixator

The patients were allowed to walk with 2 elbow crutches and bear partial weight on the limb from the 1st postoperative day onward. A gradual increase in weight bearing was allowed as the pain subsided. If the wounds were healing well, the patient was discharged home on postoperative day 1. Follow-up radiographs were taken on the day of surgery, then 2 weeks and 6 weeks after surgery, and every 4 weeks thereafter until union. Bone union was determined based on radiological (callus, bone trabeculae crossing the fracture line, or cortical continuity) and clinical evidence (no pain on physical examination, no pathological mobility of the bone fragments, painless weight bearing). If clinical and radiological evidence of union was present, the fixator was loosened at the connectors between the calcaneal semi-ring and the distal leg ring. The patient was allowed to walk, bearing full weight on the operated limb, and another follow-up radiograph was taken 7 days later. If there was no secondary displacement of the bone fragments and there was clinical and radiographic evidence of union, the Ilizarov external fixator was removed.

Variables

In this study, we assessed the following clinical and radiological parameters: pain severity using a visual analogue scale (VAS), American Orthopedic Foot and Ankle Society (AOFAS) scores, patient satisfaction with treatment, use of analgesics, period of time that the Ilizarov fixator was maintained on the lower limb, length of hospital stay, duration of surgery, patient's declared willingness to choose the same treatment again, complications, degenerative changes, Böhler angle, inflection angle, and Gissane's angle. The evaluated parameters were analyzed based on the available medical and radiological records and questionnaires completed by patients and doctors during a long-term follow-up visit.

Measurement

Pain severity was assessed with a 10-point VAS. Functional aspects were assessed with a 100-point AOFAS scale.[16] This tool helps evaluate ankle pain, range of motion, stability, and function.

The level of satisfaction with treatment was assessed on a 4-point scale: highly satisfied, satisfied, moderately satisfied, and dissatisfied.

We also assessed how many patients would choose the same treatment method again and how many patients were taking analgesic medications (tramadol, non-steroidal anti-inflammatory drugs (NSAIDs) and paracetamol) prior to surgery and at the time of their final long-term follow-up visit. The duration of Ilizarov treatment was expressed in days. The length of hospital stay was also measured in days. The duration of surgery was measured from the beginning to the end of the procedure and was expressed in minutes. The following complications were considered in our analysis: superficial pin-site infections, deep infections, skin and subcutaneous tissue necrosis, delayed wound healing, edema, necessity for reoperation, need for other procedures (arthrodesis, osteotomy or amputation), vascular injury, nerve injury, need for orthopedic footwear or shoe inserts following treatment, destabilization of the fixation, implant breakage, secondary displacement of the bone fragments, and nonunion. Possible degenerative changes were assessed based on radiographs taken at the long-term follow-up visit. The joints assessed for degenerative changes were the ankle joint, the talocalcaneal joint, the talonavicular joint, and the calcaneocuboid joint.[17] The Böhler angle, defined as the angle between a line joining the highest point of the anterior process of the calcaneus and the highest point of the posterior articular facet and a line joining the highest point of the posterior articular facet with the highest point of the calcaneal tuberosity, was assessed on lateral radiographs of the foot; normal values are 20–40°. The inflection angle, also assessed on lateral radiographs of the foot, was defined as the angle formed by the calcaneal tuberosity, the cuboid bone and the metatarsal heads (normal values: 145–150°). Gissane's angle, defined as the angle between the downward and upward slopes of the calcaneal superior surface, was also assessed on a lateral radiograph of the foot; normal values are 120–145°.

Bias

To avoid any source of bias, the measurements were recorded separately for every patient.

Study size

Application of the inclusion and exclusion criteria yielded 27 patients: 2 women and 25 men aged 28–73 years (mean age 50.5 years) included in our analysis.

Statistical analyses

The data were statistically analyzed using Statistica v. 13.1 (StatSoft Inc., Tulsa, USA). The Shapiro–Wilk test was used to check for normality of distribution. The Wilcoxon signed-rank test was used to compare quantitative variables. Bonferroni correction was used for multiple comparisons. The significance level was set at $p < 0.016$.

Results

Follow-up

The follow-up period ranged from 2 years to 5 years and 2 months (mean follow-up 3 years and 2 months).

Visual analogue scale

Following treatment, the mean VAS pain score was 2.3 (0–6). Prior to surgery, all patients were taking analgesics in comparison with only 2 patients (7.4%) at their long-term follow-up appointment. Eleven patients (40.7%) were satisfied with the treatment, and 16 patients (59.3%) were very satisfied.

American Orthopedic Foot and Ankle Society score

The mean post-treatment AOFAS score was 76.6 points (60–100). The Ilizarov fixator was removed after a mean period of 88 days (67–105 days) after surgery. The mean duration of hospital stay was 7.4 days (3–20 days). The mean duration of the procedure was 44 min (40–55 min). All patients would choose the same treatment again.

Complications

Complications were observed in 5 patients (18.5%). In all cases, these complications were superficial pin-site infections. In all patients, these infections were successfully treated with oral antibiotics and wound dressings. We observed no cases of deep tissue infections, skin or subcutaneous tissue necrosis, delayed wound healing, edema, necessity for reoperation, necessity for other procedures (arthrodesis, osteotomy or amputation), vascular injury, nerve injury, necessity for orthopedic footwear or shoe inserts following treatment, destabilization of the fixation, implant breakage, secondary displacement of the bone fragments, or nonunion.

The long-term follow-up visit revealed degenerative changes in the talocalcaneal joint in 8 patients (29.6%). There was no evidence of degenerative changes in the ankle, talonavicular or calcaneocuboid joints.

Böhler angle

The median Böhler angle was 5.5° preoperatively and 28.5° postoperatively. This difference was statistically significant ($Z = –4.461$, $p < 0.001$) (Table 1,2, Fig. 4).

Inflection angle

The median preoperative inflection angle of 160° decreased to 145° by the time of the long-term follow-up visit.

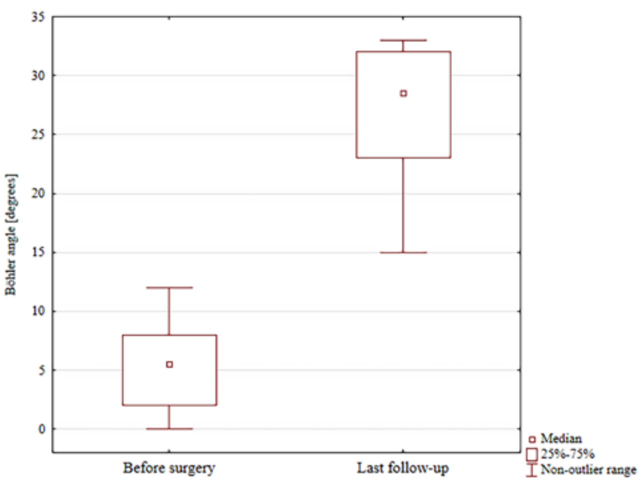

Fig. 4. Böhler angle values before and after surgery (Wilcoxon signed-rank test was used to determine significant differences)

Table 1. Detailed results before surgery and at the last follow-up

Analyzed variable		Value: before treatment	Value: last follow-up	p-value*
Böhler angle [°]	Q1	2	23	<0.001
	median	5.5	28.5	
	Q3	8	32	
Gissane's angle [°]	Q1	113	137	<0.001
	median	119	143	
	Q3	131	157	
inflection angle [°]	Q1	150	140	<0.001
	median	160	145	
	Q3	170	150	

* Wilcoxon signed-rank test; Q1 – 1st quartile, Q3 – 3rd quartile

Table 2. The results of checking the normality of the data distribution (Shapiro–Wilk test) of the difference in values variables before and after surgery presented in Fig. 4–6.

Variables	W	p-value
Böhler angle [°]	0.83553	0.01
Gissane's angle [°]	0.85691	0.033
Inflection angle [°]	0.84071	0.014

W – the test value.

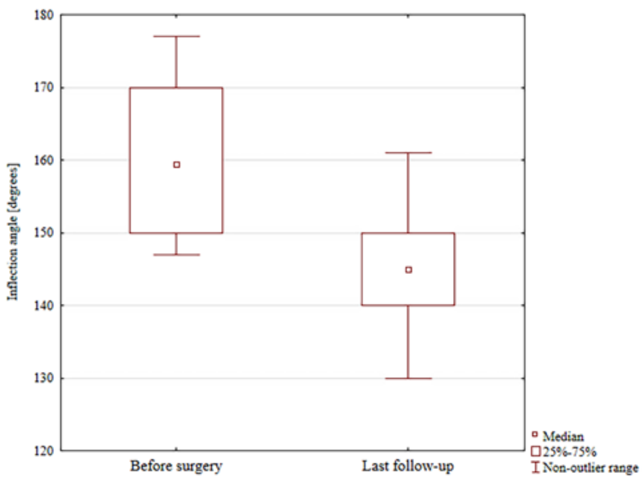

Fig. 5. Inflection angle before and after surgery (Wilcoxon signed-rank test was used to determine significant differences)

This difference was significant ($Z = –3.9101$, $p < 0.001$) (Table 1,2, Fig. 5).

Gissane's angle

The median preoperative Gissane's angle of 119° increased significantly to a mean postoperative value of 143° ($Z = –4.384$, $p < 0.001$) (Table 1,2, Fig. 6).

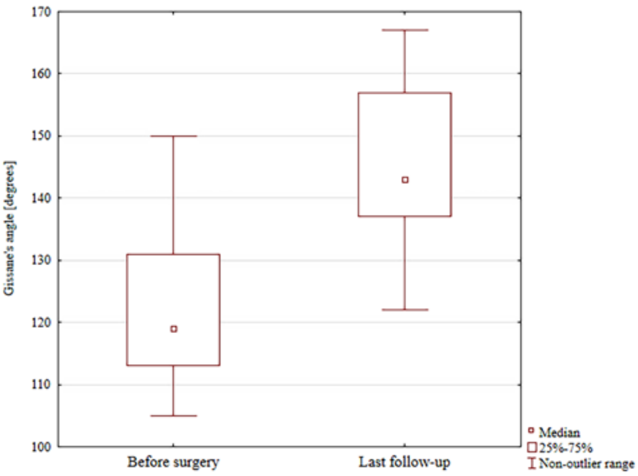

Fig. 6. Gissane's angle before and after surgery (Wilcoxon signed-rank test was used to determine significant differences)

Discussion

We conducted a detailed assessment of the clinical and radiological outcomes of using a modified Ilizarov fixator for the treatment of intra-articular calcaneal fractures. We observed good clinical outcomes and improved postoperative radiological parameters, such as the Böhler angle, the inflection angle and Gissane's angle, which supports our research hypothesis.

Most orthopedic surgeons use an open surgical approach for the treatment of intra-articular calcaneal fractures, which may be associated with high rates of complications, particularly superficial and deep tissue infections, delayed wound healing, and skin and subcutaneous tissue necrosis.[2–4,6–9,12–14,18–20] Using an open approach for the treatment of intra-articular calcaneal fractures is controversial due to high rates of limited range of motion, development of post-traumatic arthritis, infections, and delayed wound healing.[7] The Polish modification of the Ilizarov method for the treatment of intra-articular calcaneal fractures enables closed reduction, which is an advantage of this technique. Closed reduction lowers the risk of complications, shortens the duration of surgery and makes the procedure easier to perform.

Previous reports of calcaneal fracture management with the Ilizarov method mentioned the insertion of at least 3 Kirschner wires into the foot.[2,3,5–9,12–14,18–20] A higher number of implants inserted into the bones of the foot may further increase the risk of complications.[2,4] The modified Ilizarov method evaluated in our study requires only 1 Kirschner wire to be inserted into the calcaneus. The spatial configuration of Ilizarov external fixators presented by other authors for the treatment of calcaneal fractures is often complicated, bulky and burdensome for patients.[2,3,5–7,9] Usually, the Ilizarov external fixators seem to be arranged this way to improve bone fragment stability and achieve good fracture reduction.[2,3,5–7,9] Normal, anatomical repositioning of the bone fragments is believed to be the key factor for achieving good treatment outcomes in calcaneal fractures.[1,2,4–7] A normally shaped calcaneus determines the normal course of the pre-swing phase of gait.[4] Anatomical repositioning of the bone fragments and calcaneus reconstruction helps recreate normal anatomical relations of the foot structures and restores normal biomechanics.[1,2,4,6]

Our study shows that the evaluated modified Ilizarov external fixator, which requires only 1 Kirschner wire to be inserted into the calcaneus, is sufficient to achieve good clinical and radiological outcomes in the treatment of calcaneal fractures. This Polish modification of the Ilizarov method ensures sufficient bone fragment stability to achieve union and correct bone fragment alignment and to restore calcaneal shape and structure. This is achieved through ligamentotaxis and the appropriate arrangement of the connectors joining the foot semi-ring and the distal leg ring (which allows for bone fragment distraction and dorsal repositioning). The corrected position and traction exerted by the most proximal and dorsal fragments of the calcaneus fixated using 1 Kirschner wire indirectly repositioned all the remaining bone fragments. The joint distraction, or arthrodiastasis, of the ankle joint and the talocalcaneal joint enabled by the Ilizarov fixator, may reduce the development of degenerative changes and reduce pain, which may result from arthrodiastasis-stimulated chondrocyte regeneration.[2,4,7]

There have been no studies assessing VAS pain scores following the treatment of calcaneal fractures using the Ilizarov method. Muir et al., who conducted a systematic review to analyze the treatment of calcaneal fractures with an external fixator, reported persistent pain in 36.7% of patients following treatment.[2] In our study, the mean post-treatment VAS pain intensity was rated at 2.3, which is a good outcome.

The systematic review by Muir et al. yielded a mean AOFAS score of 77.5.[2] In an 18-patient study conducted by McGarvey et al., the mean AOFAS score was 66.[3] Emara and Allam evaluated 12 patients after calcaneal fractures treated with the Ilizarov method and reported a mean AOFAS score of 88.2.[6]

Ali reported a mean AOFAS score of 68 in a group of 25 patients.[9] A group of 10 patients assessed by Li et al. had a mean AOFAS score of 80.[10] The 16 patients evaluated by Mauffrey et al. had a mean AOFAS score of 80.[13] In our study, the mean post-treatment AOFAS score was 76.6, which is consistent with the data found in the literature[2,3,6,9,10,13] and indicates good clinical and functional outcomes of managing calcaneal fractures with the Polish modification of the Ilizarov method.

There are no available literature reports on the level of patient satisfaction with calcaneal fracture treatment with the Ilizarov method. In our study, 40.7% of the patients were satisfied with their treatment, and the remaining 59.3% were very satisfied with their treatment. The Polish modification of the Ilizarov fixator requires the insertion of a single Kirschner wire into the calcaneal bone and attaching it to the semi-ring, which leaves the midfoot and forefoot wire free. The Ilizarov external fixators used by other authors often take up more space, involve the entire foot, and require the insertion of at least 3 Kirschner wires into the foot.[2,3,5–9,12–14] The Polish modification to the fixator structure is the most advantageous spatial configuration in comparison with prior ones; it is also better tolerated by patients and less burdensome, and it produces higher levels of patient satisfaction with treatment.

There are no studies assessing the use of analgesics after Ilizarov treatment of calcaneal fractures. In our study, all patients had been taking analgesics before surgery, whereas by the time of their long-term follow-up visit, only 2 patients (7.4%) required analgesic treatment, indicating good long-term outcomes.

In the group of 33 patients evaluated by McGarvey et al., the Ilizarov external fixator was removed after a mean of 3 months after surgery.[3] In the group of 11 patients evaluated by Koprowski et al., the fixator was used for a mean of 3 months.[4] Emara and Allam, who evaluated 12 patients, removed the Ilizarov fixator after 3 months.[6] In our study, the Ilizarov fixator was removed after a mean of 88 days after surgery, which is consistent with the duration of Ilizarov treatment reported by other authors.[3,4,6]

In the study by Koprowski et al., the mean duration of hospital stay was 14.3 days in the younger age group and 7–10 days in the older age group of patients.[4] The patients in our study were hospitalized for a mean of 7.4 days, which is better than the duration of hospital stay reported by other authors.[4]

There have been no studies assessing the duration of surgery in the treatment of calcaneal fractures with the Ilizarov method. In our group of patients, the mean duration of surgery was 44 min, which is a good result that indicates a swift procedure. Nonetheless, some authors have described calcaneal fracture reduction and fixation with the Ilizarov method as a long and complex procedure.[2,3,5–7,9] The Polish modification of this method of calcaneal fracture treatment involves the insertion of a single implant into the foot, as opposed to the multiple implants typically required in other techniques. Furthermore, it does not necessitate an open surgical approach. This helps shorten the time of surgery and makes the method less complicated than what tends to be described in the literature.[2,3,5–7,9]

No other authors have evaluated patient willingness to choose the same method of treatment again after undergoing calcaneal fracture treatment with the Ilizarov method. All our patients declared their willingness to choose the same treatment method again if presented with a choice.

Muir et al., who conducted a systematic review of calcaneal fracture treatment with external fixators, reported persistent post-treatment pain in 36.7% of patients, limited mobility in 81% of patients, pin-site infection in 22.6% of patients, and the need to use orthopedic footwear or shoe inserts by 13.9% of patients after treatment.[2] In another study, McGarvey et al. reported limited range of motion in 80% of patients, with other post-treatment complications affecting 33.3% of patients; none of the patients required any additional procedures (arthrodesis, osteotomy or amputation).[3] Out of the 12 patients treated with the Ilizarov method and evaluated by Emara and Allan, 66.6% of the patients developed complications, which were pin-site infections in 16.6% of cases.[6] In the group of 10 patients assessed by Li et al., pin-site infections were reported in 20% of the patients.[10] Paley et al. reported pin-site infections in 14.3% out of the 7 evaluated patients, and the total proportion of patients who developed complications was 57.1%.[12] In our study, 5 patients (18.5%) developed complications; however, none of our patients required any additional procedures (arthrodesis, osteotomy or amputations). Superficial pin-site infections affected 18.5% of our patients, which is consistent with the data reported in the literature.[2,6,10,12] None of the patients in our study developed deep infections, skin or subcutaneous tissue necrosis, delayed wound healing, edema, vascular injury, nerve injury, or the need for orthopedic footwear or shoe inserts after treatment. The patients in our study underwent closed reduction, which may have lowered the complication rates in comparison with those reported by other authors.[2,3,6,10,12] The modified method of calcaneal fracture fixation used in our study allowed for walking and partial weight bearing on the operated limb as early as the 1st postoperative day. There were no cases of destabilization of the fixation, wire breakage, secondary displacement of the bone fragments, nonunion, or the necessity for reoperation. These results indicate good bone fragment stability. However, some authors, despite the use of at least 3 Kirschner wires for foot fixation, recommend bearing no weight on the operated foot for 3–10 weeks,[6,8,9,13] which may negatively affect treatment outcomes by restricting joint mobility, increasing the rates of edema, degenerative changes, and lowering the level of satisfaction with treatment.[2–4] A long period of reduced weight bearing on the operated limb may limit patient rehabilitation and lead to pain.[4]

Some authors have reported the development of degenerative changes after treatment of calcaneal fractures with the Ilizarov method; however, they did not specify the exact proportion of patients affected.[3,4] The possibly altered shape of the calcaneus leads to asymmetric load distribution through the ankle joint and the talocalcaneal joint and may result in the development of arthritis.[4] Evidence of osteoarthritis has been reported in 44–68% of patients after calcaneal fracture treatment.[2,9] Out of the 25 patients analyzed by Ali et al., 44% developed degenerative changes in the talocalcaneal joint and 24% in the calcaneocuboid joint.[9] In our study, 29.6% of the patients developed degenerative changes, within a mean period of 3 years and 2 months after treatment. In all cases, the degenerative changes developed in the talocalcaneal joint. There was no evidence of degenerative changes in the ankle joint, talonavicular joint or calcaneocuboid joint. The Polish modification in the Ilizarov treatment of calcaneal fractures makes it possible to perform arthrodiastasis of the talocalcaneal and ankle joints,[4] which may limit the development of degenerative changes.[4,7] A long period of immobilization and reduced weight bearing in the treatment of calcaneal fractures is associated with an increased risk of complications, joint degeneration and stiffness, and poor treatment outcomes.[1,3] Our patients were allowed to bear weight on the operated limb very early, which may have limited the development of degenerative changes.

One study found that following open reduction and fixation with cannulated screws or a plate, the Böhler angle values improved by 16–30° in comparison with their preoperative values.[1] A systematic review of studies involving calcaneal fracture treatment with external fixators revealed the mean postoperative Böhler angle to be 24.8°.[2] In a group of 11 patients treated with the Polish modification of the Ilizarov method, the mean Böhler angle was 4° after injury and 27° after treatment.[4] In the evaluated group of 25 patients, Ali et al. observed an increase in the mean Böhler angle values from 11° before surgery to 24° after treatment.[9] The group of 10 patients assessed by Li et al. showed the mean Böhler angle value was 17.3° preoperatively and 25.9° postoperatively.[10] In 16 patients assessed by Mauffrey et al., the mean Böhler angle was 16° after the injury and 17° after treatment.[13] In our study, the median Böhler angle was 5.5° before surgery and increased significantly to reach 28.5° after surgery. The value of the Böhler angle achieved in our study is consistent with those reported by other authors.[1,2,4,9,10,13]

In the group of 11 patients assessed by Koprowski et al., the mean inflection angle was 154° prior to treatment and 147° after treatment.[4] We noted a median inflection angle of 160° before surgery, which decreased to 145° at long-term follow-up; these values are similar to those reported earlier.[4]

In the group of 10 patients evaluated by Li et al., the mean Gissane's angle was 100.5° before surgery and 109.5° after surgery.[10] Mauffrey et al., who evaluated 16 patients, reported a mean Gissane's angle of 115° before surgery and 106° after the operation.[13] In our study, the median preoperative Gissane's angle was 119°, and its value increased significantly to 143° after surgery.

The use of the Ilizarov method in the treatment of calcaneal fractures helps align the bone fragments during surgery and gradually correct their position afterwards in the case of failure to achieve normal alignment during surgery.[3,4,7] This helps achieve good radiological outcomes and reconstruction of the calcaneus. Reconstructing the normal shape of the calcaneus following a fracture helps restore normal load distribution in the foot and lowers the risk of degenerative changes.[4] The values of the evaluated radiological parameters in our group of patients were similar to those reported by other authors. The Polish modification of the Ilizarov method helps recreate the normal shape of the calcaneus and, depending on the nature of the fracture and the three-dimensional course of the fracture lines, its articular surfaces as well,[4] which is consistent with our findings. The radiographs obtained in our study showed the three-dimensional structure of the foot to be similar to normal.

The use of Ilizarov external fixators is particularly indicated in the case of calcaneal fracture with concomitant soft tissue injury, compound fractures, multiple trauma, and bilateral calcaneal fractures.[2,4,6,7]

The advantages of the Polish modification of the Ilizarov method in the management of intra-articular calcaneal fractures are the facts that it is easy to use, better tolerated by patients and minimally invasive, which minimizes soft tissue injury and reduces the risk of complications. The Polish modification of the Ilizarov method helps restore the shape and architecture of the calcaneus, which leads to normal load distribution in the foot and limits the development of post-traumatic arthritis.

Limitations

The limitations of our study include its retrospective character, which is due to the lack of possibility to assess clinical parameters prior to treatment in patients with calcaneal injury due to pain and pathological mobility of the injured calcaneus and the impossibility of predicting injury in advance. We would like to emphasize that other studies evaluating the treatment of calcaneal fractures were also retrospective in nature.[3–6,8–10,12–15,18–20] Another limitation of our study is the relatively low sample size, which was a result of several factors. One factor is the relative rarity of intra-articular calcaneal fractures; moreover, some patients lived far away from the study center and were unable to return for their final follow-up appointment. However, most other studies evaluating clinical and radiological parameters following calcaneal fractures also included similar, if not smaller, groups of patients.[3–6,8–10,12–15,18–20] Another limitation of our work is the lack of comparison of the results to patients with calcaneal fractures who underwent different treatment methods. Most available articles that describe the clinical or radiological results of the treatment of calcaneal fractures using the Ilizarov method[2–5,8–10,12–15,18–20] analyze the results of treatment only with the Ilizarov method, without a control group with different treatment methods. Another limitation of our study is the inclusion of patients with concomitant injuries. This was dictated by our eagerness to demonstrate the use of this modified Ilizarov method in the management of patients with calcaneal fractures and multiple other injuries and to increase the overall number of patients included in the study. Other authors also evaluated patients with calcaneal fractures, some of whom (30%) had concomitant musculoskeletal injuries.[4]

Another limitation of our work may be the disproportion in male/female distribution.

The strengths of our study are the uniform surgery protocol, the fact that the same orthopedic surgeon conducted all surgeries, the uniform rehabilitation protocol, and the fact that multiple clinical and radiographic parameters were assessed. We are currently planning a study in a larger patient population with a longer follow-up period. We also intend to prepare an article comparing the results of treating calcaneal fractures using the Polish modification of the Ilizarov method with those of a different treatment method, such as internal fixation.

Conclusions

The Polish modification of intra-articular calcaneal fracture treatment with the Ilizarov method helps achieve good stabilization of the bone fragments and restores the shape and architecture of the calcaneus.

The patients in our study exhibited lower rates of complications and degenerative changes than those reported by other authors who evaluated calcaneal fracture treatment with the Ilizarov method.

All patients in our study were satisfied or very satisfied with the treatment they received.

The patients achieved good clinical and radiological outcomes with the assessed Polish modification of the Ilizarov method for the management of intra-articular calcaneal fractures.

Data availability

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

Consent for publication

Not applicable.

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